MINISTRY OF
INDUSTRY AND TRADE

EU - VIET NAM SUSTAINABLE ENERGY
TRANSITION PROGRAMME (SETP)

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UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Project "Accelerating energy efficiency (EE) in large industries through energy management system, system optimisation and the promotion and adoption off EE in SMEs" (IEEP)

END-USER TRAINING
INDUSTRIAL STEAM SYSTEM OPTIMISATION

Ha Noi, 21 - 22/03/2024

AGENDA

Expert Training on Steam System Optimisation
21 - 22 March 2024
Adonis Hotel – 55 Quang Trung, Nguyen Du ward, Hai Ba Trung dist., Ha Noi

Day 1: 21 March 2024

Time	Contents	Speakers
8.00-8.30	Registration and welcome	
8.30-8.40	Participants Introduction	Representative of UNIDO Project Office
8.40-8.50	Opening speech	Representative of the Project Management Board
8.50-9.00	Introduction of Trainers	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
9.00-10.30	Section 1: Fundamentals - Introduction to "Systems Approach" - Review of steam system fundamentals – thermodynamics	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
10.30-10.45	**Tea break**	
10.45-12.00	Section 2: Steam System Scoping Tool (SSST) - Steam System Optimization Opportunities - SSST - Hands-On Exercise on SSST	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
12.00-13.15	**Lunch at the Hotel**	
13.15-15.15	Section 3: US DOE MEASUR tool - Overview of US DOE MEASUR - MEASUR Calculators/ Assessments - 3-header Student Hands-On Exercise	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
15.15-15.30	**Tea break**	
15.30-17.00	Section 4: US DOE MEASUR tool (continued) - Fundamentals of Turbines - Modeling Backpressure/ Condensing Turbines in MEASUR - Hands-On Student Exercise	Mr. Riyaz Papar Mr. Nguyen Xuan Quang

Day 2: 22 March 2024

Time	Contents	Speakers
8.00-8.30	Registration and welcome	
8.30-9.50	- Question / Answers - Review of Day 1	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
8.50-10.15	Section 5: SSO – Generation Area	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
10.15-10.30	**Tea break**	
10.30-11.15	Section 6: SSO – Distribution Area	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
11.15-12.00	Section 7: SSO – EndUse Area	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
12.00-13.15	**Lunch at the Hotel**	
13.15-14.15	Section 8: SSO – Condensate Recovery Area	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
14.15-15.15	Section 9: SSO – Cogeneration Area	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
15.15-15.30	**Tea break**	
15.30-15.45	Section 9: SSO – Cogeneration Area	Mr. Riyaz Papar
15.45-16.15	Wrap-Up	Mr. Riyaz Papar Mr. Nguyen Xuan Quang
16.15-16.45	Course Evaluation & Feedback	Mr. Riyaz Papar
16.45-17.00	Closing remarks	Representative of UNIDO Project Office

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Accelerating energy efficiency (EE) in larger industries through energy management system, system optimization and the promotion and adoption of EE in SMEs – (IEEP project)

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Industrial Steam System Optimization (SSO) - 2-Day End-User Training

Developed by:

Riyaz Papar, P.E., CEM, Fellow – ASME, ASHRAE; C2A Sustainable Solutions, USA

Greg Harrell, Ph.D., P.E.; Energy Management Services, USA

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Acknowledgments

- UNIDO Team – Vienna, Austria
- UNIDO Team – Thailand
- United States Department of Energy, USA
- Oak Ridge National Laboratory, USA

Riyaz Papar, P.E., CEM, Fellow – ASME, ASHRAE

Education:

- M.S. (Mechanical Engineering), University of Maryland, College Park
- B.Tech. (Mechanical Engineering), Indian Institute of Technology, Mumbai

Professional Experience:

- CEO, C2A Sustainable Solutions, USA
  - Industrial Thermal System Optimization, Sustainability & Decarbonization
- Other Past Employers - Hudson Technologies Company, Enron Energy Services, Lawrence Berkeley National Laboratory, Energy Concepts Company (all in USA)

Other Qualifications & Affiliations:

- US DOE Steam & Process Cooling BestPractices Lead Instructor & Technical Advisor
- US DOE Steam Energy Expert
- UNIDO Energy Expert – Steam, Refrigeration & Chillers and Waste Heat Recovery
- Chair, ASME Process Industries Division, 2003-04
- Chair, ASHRAE Technical Committee 8.2: Centrifugal Machines, 2009-10
- Chair, ASHRAE Technical Committee 1.10: Cogeneration Systems, 2010-11

Contact Information

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Training Objectives

- Help industry assess steam systems and achieve energy and cost savings through
  - Proper operation and controls
  - System maintenance
  - Appropriate process uses of steam
  - Cogeneration and
  - Application of state-of-the-art technologies
- Introduce and demonstrate the functionality of US DOE publicly available steam system optimization assessment software tools

General Summary

- The 2-Day End-User training begins by defining the Systems Approach and how it applies for optimizing an industrial and/or institutional steam system
- The training covers the operation of typical industrial steam systems that include
  - Generation
  - Distribution
  - End-uses / Combined Heat & Power and
  - Condensate recovery

General Summary

- The training identifies *performance improvement opportunities* that lead to the optimization of the overall steam system
- The workshop discusses methods of system efficiency improvements, methodologies for quantifying energy and cost savings from these improvements, aspects of implementation and continuous improvement programs

General Summary

- Demonstration and hands-on functionality and use of the US DOE's Steam BestPractices Program. These include:
  - Steam System Scoping Tool (SSST)
  - US DOE MEASUR (MEASUR)
  - 3E-Plus insulation appraisal software
- Software tools are free and available for download from the websites as well as online usage
- Field examples and applications of using these software tools in an industrial steam system energy assessment

Training – Outline Day 1

- Laptop setup for all attendees – software tools and program files
- Presentation on the UNIDO Industrial Energy Efficiency Project
- Introduction to "Systems Approach"
- Review of steam system fundamentals – thermodynamics
- Review of the US DOE Steam System Scoping Tool (SSST)
- Student Exercise – Evaluation of an industrial plant steam system using the SSST and identifying energy savings areas
- Coffee / Tea Break

Training – Outline Day 1

- Example Steam system
- Identification of impact boiler – example from industrial plant
- Steam Cost Indicator
- Review of the US DOE's Manufacturing Energy Assessment Software for Utility Reduction (MEASUR) Tool
- MEASUR Calculators

Training – Outline Day 1

- Building a steam system Model in MEASUR
- Calculation of boiler efficiency using field measurements
- Boiler Losses
  - Shell Loss
  - Blowdown Loss
  - Stack Loss
- Lunch Break

Training – Outline Day 1

- Complete building a steam system Model in MEASUR
- Marginal Steam Cost Discussion / Comparison
- Coffee / Tea Break
- Fundamentals of Turbines
- Modeling Backpressure Turbines in MEASUR
- Modeling Condensing Turbines in MEASUR
- Review of final model
- Adjourn

Training – Outline Day 2

- Review Day 1 material
- Questions and Answers on material covered on Day 1
- Steam System Optimization – Generation Area
  - Boiler Efficiency Improvement
  - Blowdown Management
  - Blowdown Energy Recovery
  - Feedwater Economizers / Combustion AirPreheaters
  - Excess Air Control
  - Fuel Switching
- Hands-On Student Exercises
- Coffee / Tea Break

Training – Outline Day 2

- Steam System Optimization – Distribution Area
  - Steam Leaks
  - Heat Transfer Loss Through Insulation
- 3E Plus Insulation Evaluation Software
- Steam System Optimization – End-Use Area
  - Steam Demand (End Use)
- MEASUR Steam Demand Savings Projects
- Lunch Break

Training – Outline Day 2 (cont.)

- Steam System Optimization – Condensate Recovery Area
  - Steam Trap Management Program
  - Evaluation of Condensate Recovery Systems
  - Condensate Flash Tanks
  - Condensate Tank Vents
- Student Exercise – Complete examples on condensate recovery and condensate flash steam recovery using the MEASUR software tool

Training – Outline Day 2 (cont.)

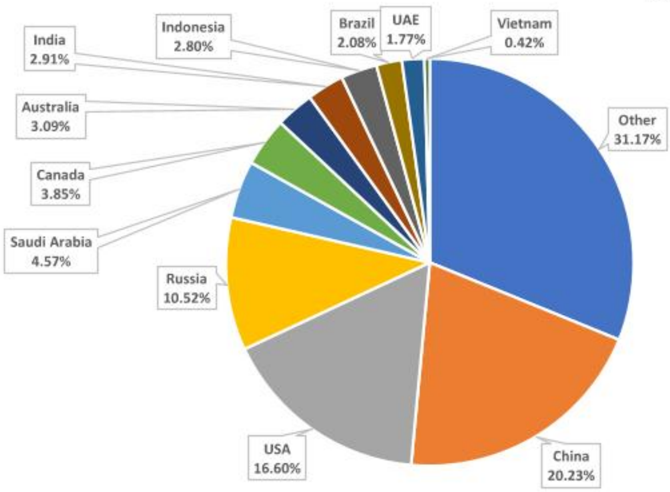
- Steam System Optimization – Combined Heat & Power Area
  - BackPressure Turbine – PRV Operations
  - MEASUR Turbine Projects Economics
  - Condensing Turbine Impacts
  - MEASUR Condensing Turbine Projects
- Coffee / Tea Break
- Conclusions
- Tools & Resources

Personal Goals

- Introduction of attendees
- Any major issues or concerns as regards the course material, timeline, etc.
- Identification of possible areas which need more in-depth coverage based on the interests of the attendees

Overview:

- **Overall Energy Usage**
- **Steam Energy Usage**
- **The Systems Approach**
- **Steam System Optimization (SSO)**

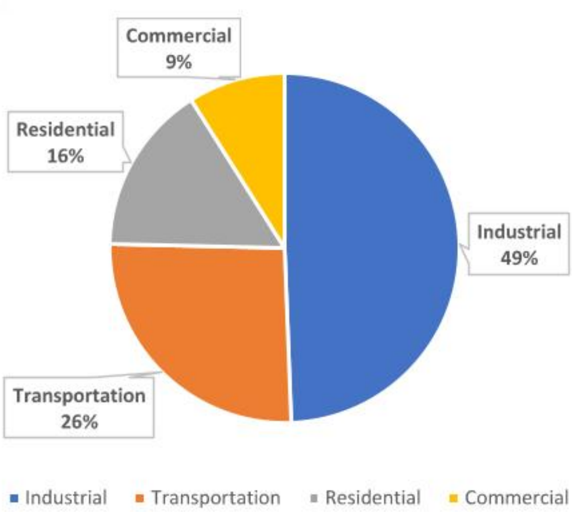


World's Energy Production

1 quad Btu = 1.055 EJ

Source: US DOE EIA; International Energy Agency

Total World Energy production ~ 620 quad Btu



Industrial Energy = ½ World's Energy

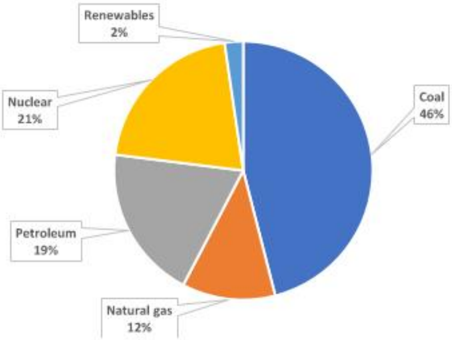
1 quad Btu = 1.055 EJ

Source: US DOE EIA; International Energy Agency

Total World Energy production ~ 620 quad Btu

Vietnam Energy Production – Consumption

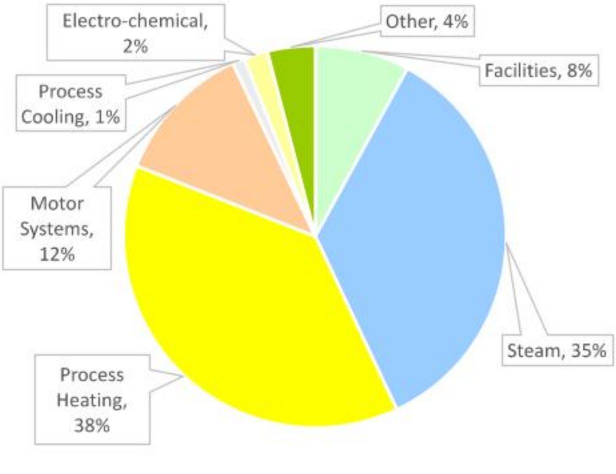
- Vietnam imports – Coal, Natural gas, Petroleum and other liquid fuels



Production: 2.56 quad Btu

Consumption: quad Btu

Source: International Energy Agency Data - 2019



Typical Industrial Plant Energy Consumption

Note: Does not include off-site losses

Source: DOE/EIA Monthly Energy Review 2004 (preliminary)

Heavy Steam Users

- Petrochemicals
- Petroleum Refining
- Forest Products (Pulp & Paper)
- Food & Beverage
- Plastics
- Rubber
- Textiles
- Pharmaceuticals
- Manufacturing Assembly

Medium Steam Users

- Large commercial heating
- Breweries
- Laundries
- Bakeries
- Cooking
- Metal Fabrication
- Large chiller systems

Small Steam Users

- Electronics
- Paint booths
- Humidification systems

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Why Use Steam?

- Extremely efficient as a heating source – constant temperature, highest heat transfer (condensing) coefficients
- Extremely cost effective to distribute to point-of-use
- Can be controlled very accurately
- A very flexible energy transfer medium – can be used for process heating as well as power generation
- Technology and applications are tried and proven at large as well as small-scale
- Significant system benefits!

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The Systems Approach

- Key to cost-effective plant utility system operations and maintenance
- Pay attention to the system as a whole, not just to individual pieces of equipment
- Analyze both the supply and demand sides of systems and how they interact
- Most industrial systems will need a Systems Approach for proper analysis
- Will lead to significantly higher energy and cost savings than a “component level analysis”

The Systems Approach

15 kW motor efficiency = 91%

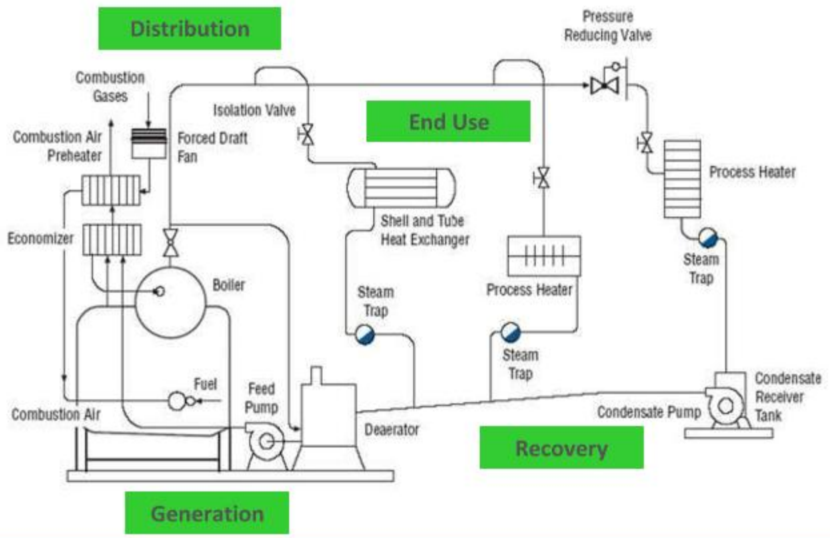
Combined motor &
pump efficiency = 59%

System efficiency = 13%

Source: US DOE BestPractices Program; Courtesy: Don Casada, Diagnostic Solutions, USA

The Systems Approach

- **Establish** current system conditions, operating parameters, and system energy use
- **Investigate** how the total system presently operates
- **Identify** potential areas where system operation can be improved
- **Analyze** the impacts of potential improvements to the plant system
- **Implement** system improvements that meet plant operational and financial criteria
- Continue to **monitor** overall system performance



Generic Steam System

Source: US DOE Steam Best Practices Program

Industrial Steam System Optimization

- Needs to follow a SYSTEMS Approach
- Focuses on how steam system energy is managed in a plant
- Industrial steam demands change over time and operations of steam system assets should be optimized on a continuous basis
- BestPractices during design, procurement, operations and maintenance must be followed
- Understanding of the fundamentals and tools and resources available is key for a SSO program

Identified Savings per Plant Summary (in US)

System Type (No. of SENAs)	Average Recommended Source Energy Savings (GJ/plant per year)	Average Percent Source Energy Savings Recommended (%)	Average Recommended Cost Savings ($/plant per year)	Average Natural Gas Savings Recommended (GJ/plant per year)	Average CO2 Savings Recommended (Tons/plant per year)
Compressed Air (127)	30,800	2.2	$177,000	440	1,700
Fans (40)	206,900	3.1	$1,151,000	38,400	9,000
Process Heating (213)	246,300	11.2	$1,582,000	187,400	13,300
Pumps (80)	42,400	1.2	$219,000	1,250	2,400
Steam (313)	270,100	7.0	$2,075,000	220,000	18,000
Multi-System-Paper (20)	420,200	4.7	$2,782,000	217,900	21,000

Source: Oak Ridge National Laboratory, USA

Steam System Fundamentals

- Steam System Components
- Thermodynamics – Steam Properties
- Conservation of Mass
- Conservation of Energy
- Fuels
- Steam System Optimization Opportunities

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Steam System Components

- **Generation**
  - Boiler
  - Boiler auxiliaries
  - Water treatment equipment
  - Deaerator
  - Feedwater Pumps
  - Fuel storage and handling equipment
- **Distribution**
  - Steam piping
  - Pressure reducing stations
- **End-use**
  - Steam turbines
  - Heat exchangers
  - Live steam injection
  - Stripping columns
  - Evaporators, etc.
- **Recovery**
  - Steam traps
  - Condensate recovery and return system
  - Condensate pumps

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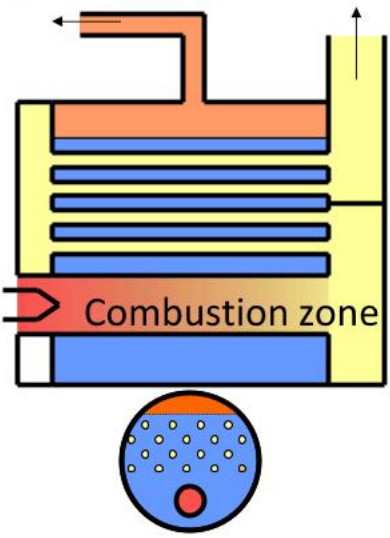
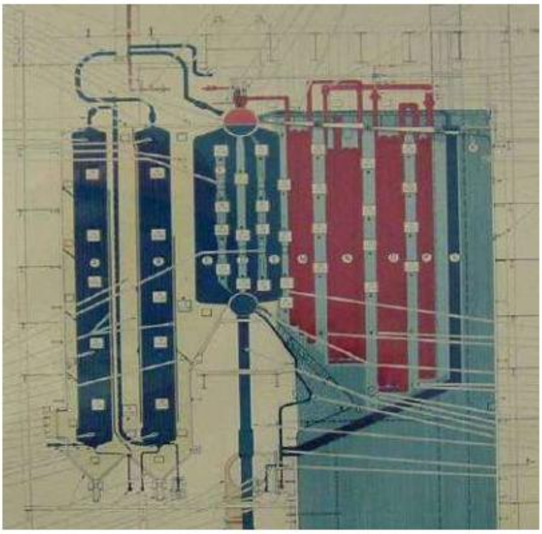
Fire-Tube Boiler



- Steam pressure limited
  - Typical 20 bars maximum
- Steam flow rate limited
  - Typical 1,200 BHp maximum
    - 20 tons/hr
- Saturated steam output
- One inherent efficiency advantage over water tube type – shell loss is minimal
- Generally manufactured offsite
- Many different styles

Source: US DOE Steam BestPractices Program

Fire Tube Boilers



Water-Tube Boiler

- Operating pressures range from atmospheric to in excess of 250 bars
- Steam production ranges from 2 Tph to 5,000 Tph
- Saturated or superheated steam output
- Constructed onsite or offsite
- Many different styles
- Compact units now on the market!

Source: US DOE Steam BestPractices Program

Water Tube Boilers

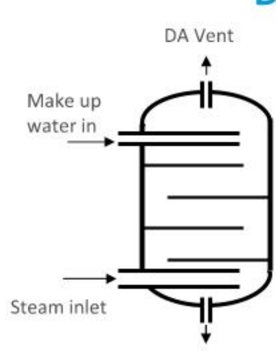
Boilers & Boiler Auxiliaries

- Fans - Air flow configuration
  - Forced draft
  - Induced draft
  - Balanced draft
- Combustion air preheaters
- Feedwater economizers / condensing economizers
- Fuel flow valves and combustion controls
- Excess air controls
- Sensors
- Soot blowers – steam or compressed air
- Pollution control equipment

Fuel Storage & Handling Equipment

- Mainly for solid and liquid fuels
  - Primary
  - Back-up / Standby

Deaerator



- Removes dissolved oxygen from make-up water and condensate
- Boiler integrity
- Several different styles
  - Spray type
  - Tray type
- Maybe combined with feedwater heater and storage
- Will always have a steam vent!

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Pumps

- Boiler Feedwater (BFW)
- Condensate
- Make-up water
- Other auxiliary services

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Water Treatment Equipment

- Extremely important boiler water chemistry
- Integrity of boiler
- Depends on boiler pressure and water quality
- Several options
  - Softening
  - Dealkalization
  - Demineralization
  - Reverse osmosis
  - Condensate polishing
  - Chemical treatment




Steam Piping

- Transports steam to end use
- Pipe racks
- Pressure headers
- Isolation valves
- Relief valves
- Drain points, etc

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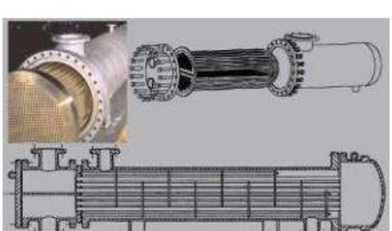
Pressure Reducing Stations

- Also known as Letdown valves
- Provide steam flow control
- Provide pressure header balancing
- Operates on a feedback loop
- Always need a bypass for emergency and repair conditions

Steam Turbines

- Devices which convert thermal energy into shaft power
- Can generate electrical power through a generator
- Can drive a mechanical equipment – fan, pump, compressor, chiller, etc.
- Different types
  - Backpressure
  - Extraction
  - Condensing
  - Combination of the above

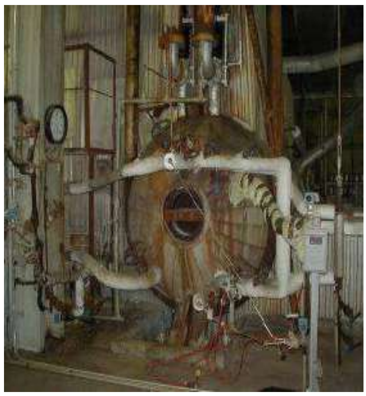


Heat Exchangers

- Different types
  - Shell & Tube
  - Plate / Frame
  - Tube in tube
  - Spiral, etc.
- Based on applications
- Steam transfers thermal energy to process fluid and forms condensate
- Industry standards for designs and applications

Other End Use Equipment

Feed Heater



Cooker

Washing, Drying & Finishing

Hot water heater

Other End Use Equipment

- Evaporators
- Reboilers (Distillation)
- Stripping columns
- Reformers
- Dryers
- Steam ejectors
- Steam injectors
- Thermocompressors




Steam Traps

- Prevent steam from escaping without transfer of heat
- Several different types of traps
  - Thermostatic
  - Mechanical
  - Thermodynamic
  - Orifice
- Application – very important
- Steam Trap Management


Flash Tanks

- Recover flash steam from condensate
- Eliminate potential condensate return problems
  - Water hammer
  - Back-pressure
  - 2-phase flow
- Blowdown flash tanks reduce temperature of water before discharging to sewer

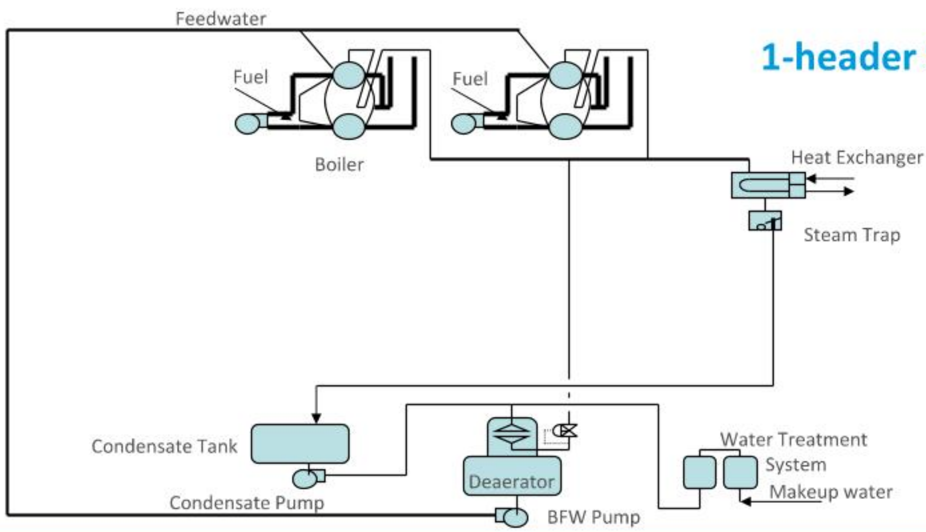
Condensate Recovery System

- Primary / Secondary
- Pumped / Pressure-driven
- Pumped – Electric-driven or Steam-driven
- Returns condensate back with the highest thermal energy to the boiler house

Condensate Tank

- Provides for a common receiver
- Typically, located above grade to provide for pump suction requirements
- May be combined with deaerator and feedwater heater and storage

1-header System



Source: US DOE Steam BestPractices Program

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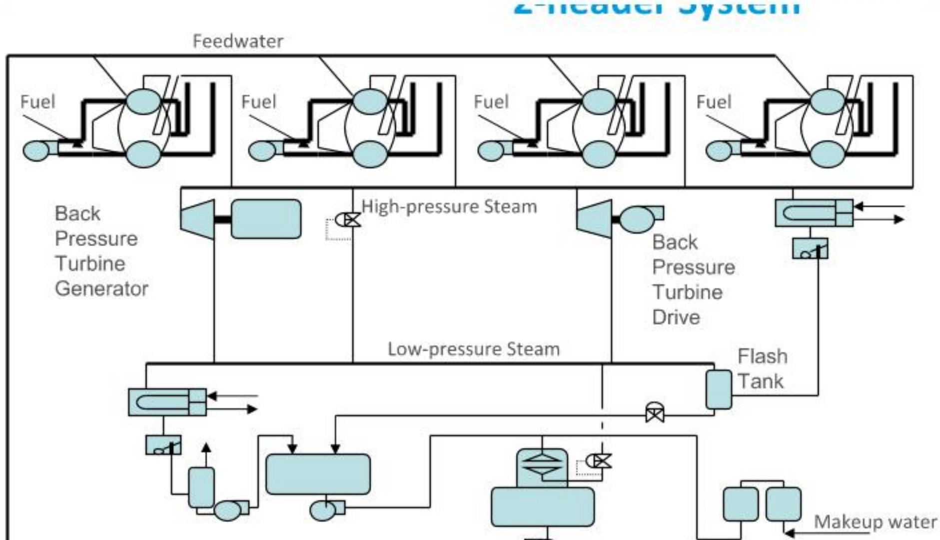
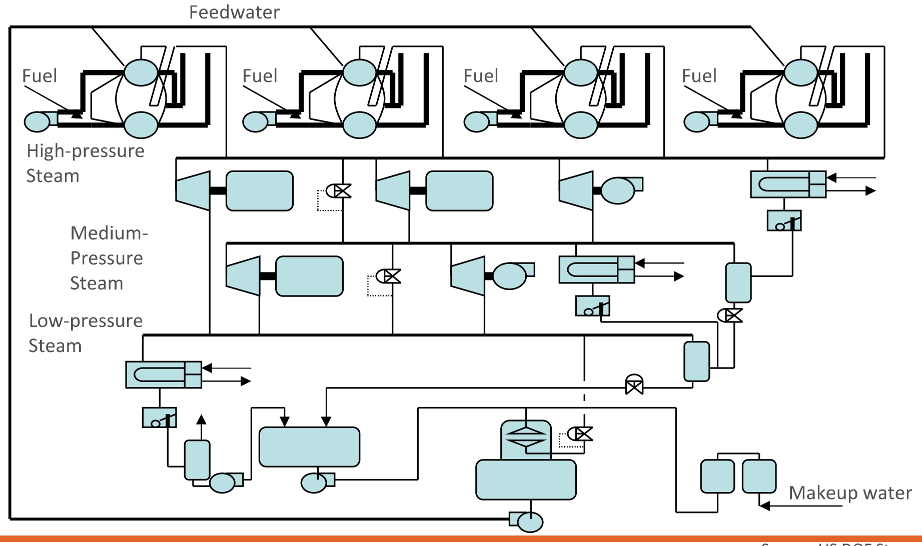
2-header System



Source: US DOE Steam BestPractices Program



Source: US DOE Steam BestPractices Program

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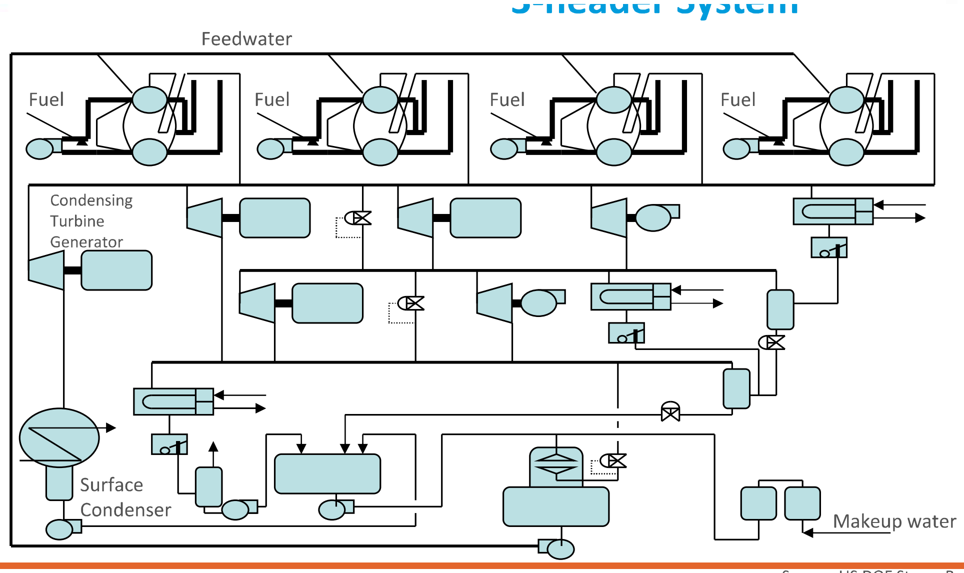


Source: US DOE Steam BestPractices Program

What is STEAM?

- Saturated or Superheated Water Vapor

When water is heated to or above it's boiling point, it produces STEAM

Liquid Water

↓

Gaseous Steam

Steam Thermodynamics

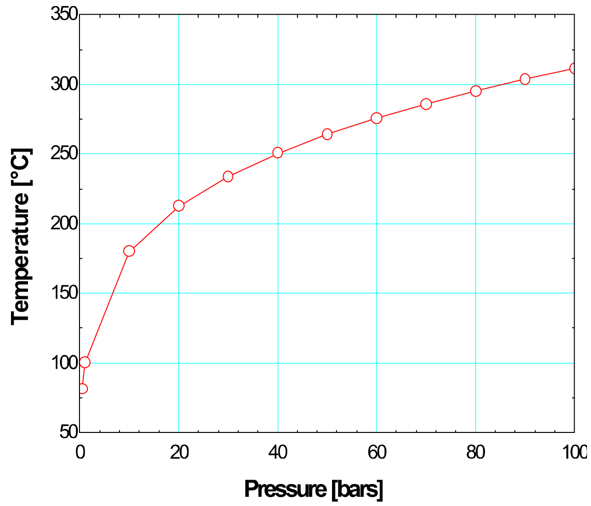
- Thermodynamic States of a Pure Substance
  - Subcooled
    - Liquid (Water)
    - Temperature and Pressure are independent
    - Energy content $\propto$ Temperature
  - Saturated
    - Liquid / 2-Phase / Vapor
    - Temperature and Pressure are **dependent**
    - $0 \leq$ Quality ≤ 1
  - Superheated
    - Vapor (Steam)
    - Temperature and Pressure are independent
    - Energy content $\propto$ Temperature & Pressure

Thermodynamic Properties of Steam

- P - Pressure (bars, atmospheres, kPa, MPa)
- T - Temperature (°C)
  - Absolute Temperature (K)
- X - Quality
- ρ - Density (kg/m^3)
- V - Volume (m^3/kg)
- H - Enthalpy (kJ, kcal)
  - h - Specific Enthalpy (kJ/kg, kcal/kg)
- S - Entropy (kJ/K, kcal/K)
  - s - Specific Entropy (kJ/kg-K, kcal/kg-K)

Thermophysical Properties of Steam

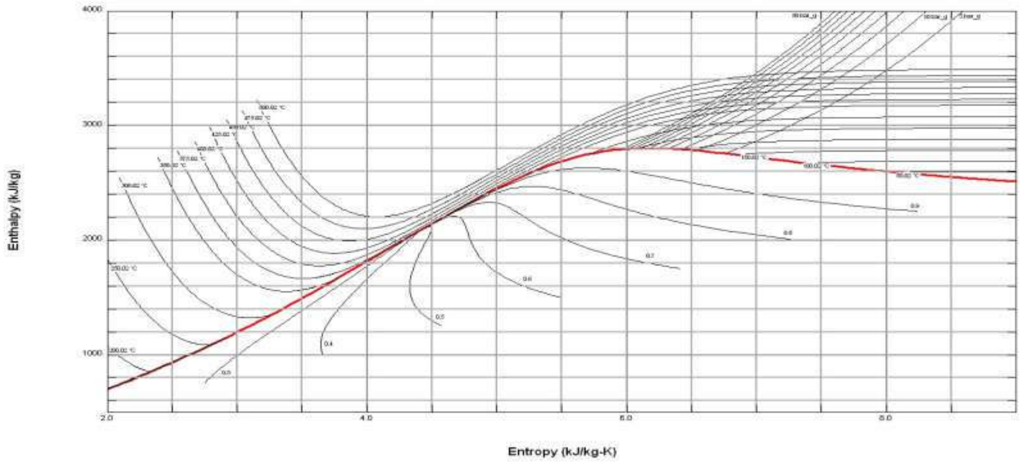
- C_p - Specific Heat at constant pressure (kJ/kg-K, kcal/kg-K)
- C_v - Specific Heat at constant volume (kJ/kg-K, kcal/kg-K)
- V_s - Velocity of sound (m/s)
- μ - Viscosity (Pa.s)
- K - Thermal Conductivity (W/m-K)



Steam Thermodynamics

- Pressure – Temperature Relationship
  - As Pressure ↑ – Temperature ↑

H-S diagram (Mollier Diagram)



Steam Thermodynamics

- Steam Tables

psteam [bars]	t_{steam} [°C]	ρ_f [kg/m3]	v_f [m3/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kgK]	s_{fg} [kJ/kgK]	s_g [kJ/kgK]
0.5	81.31	971	3.244	340.4	2,305	2,645	1.091	6.502	7.593
1.0	100	958.4	1.672	419.2	2,257	2,676	1.307	6.047	7.354
10.0	179.9	887.2	0.1945	762.8	2,015	2,778	2.139	4.447	6.586
20.0	212.4	849.9	0.09962	908.6	1,890	2,799	2.447	3.893	6.34
30.0	233.9	822	0.06667	1,008	1,795	2,803	2.645	3.54	6.186
40.0	250.4	798.5	0.04978	1,087	1,713	2,801	2.796	3.273	6.069
50.0	264	777.5	0.03944	1,154	1,640	2,794	2.92	3.053	5.973
60.0	275.6	758.2	0.03244	1,213	1,571	2,784	3.027	2.862	5.889
70.0	285.9	739.9	0.02737	1,267	1,505	2,772	3.121	2.692	5.813
80.0	295	722.4	0.02352	1,317	1,441	2,758	3.207	2.536	5.743
90.0	303.4	705.4	0.02048	1,363	1,379	2,742	3.285	2.392	5.677
100.0	311	688.6	0.01802	1,407	1,317	2,724	3.359	2.255	5.614

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Steam Thermodynamics

- Steam Properties
  - Steam Tables
    - Mollier Diagrams
  - ASHRAE Fundamentals Handbook
    - Tabulated Data
    - P-h diagram
  - Software Programs
    - Equation of State for different refrigerants
    - Engineering Equation Solver (EES)
    - Other
  - REFPROP - National Institute of Standards & Testing (NIST)
- Reference Point
  - Maybe different for different sources!!

Steam System Analysis

- Steady State Steady Flow (SSSF) analysis
  - Neglect the time dependent terms
  - Dynamic responses are not considered
  - Start-up, Shut-down and upset (or trip) conditions are neglected
- Average operating conditions are used
- Seasonality, Production rates can be dealt with "bin analysis" methodology
- IMPACT level-analysis is conducted on systems

Steam System Analysis

- In order to properly evaluate steam systems the physics of each process must be understood
  - Thermodynamics
  - Heat transfer
  - Fluid flow
- Process measurements
  - Temperatures, Pressures, Flows, etc.
- U.S.DOE Tools Suite
  - Steam System Scoping Tool (SSST)
  - US DOE MEASUR
  - Insulation evaluation software – 3E-Plus
- Commercially available software
  - Aspen Tech
  - ProSteam (KBC Linhoff March)
  - Visual MESA, etc.

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Conservation of Mass

Steady State Steady Flow

- Law: Mass is neither created nor destroyed in the control volume
- Mathematically,
  - Mass flow in = Mass flow out
- Equation format
  - $\sum M_{in} = \sum M_{out}$
- State of substance & volume flow can change

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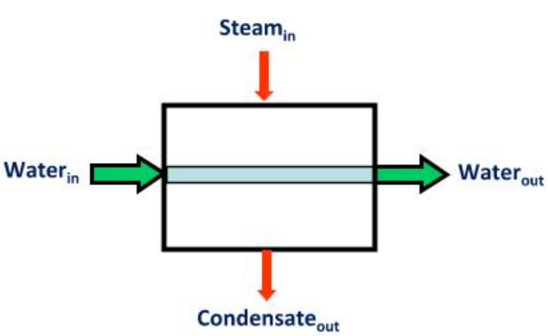
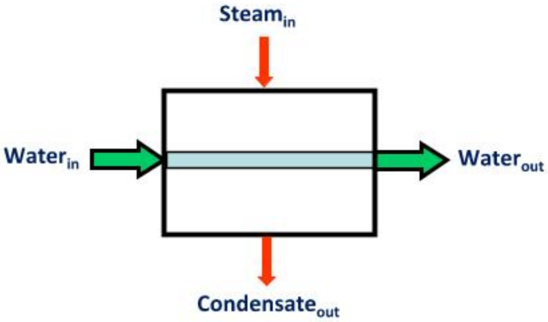
Example: F1



- A shell and tube heat exchanger is used to heat water using steam
- Water flow rate measured as 600 litres/min
- Steam flow rate is not known

Example: F1

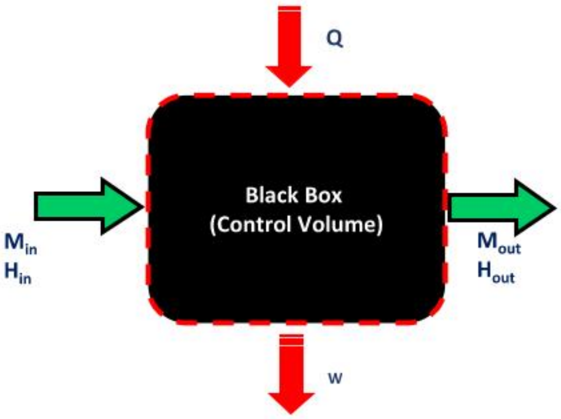


- Apply Steady State Steady Flow – Conservation of Mass
- Water side: Water flow in = Water flow out
- Steam side: Steam flow in = Condensate flow out

Example: F1

- Apply Steady State Steady Flow - **Conservation of Mass**
- Water side: Water flow in = 600 litres/min
  = 600 kg/min
  Water flow out = 600 litres/min
  = 600 kg/min
- Steam side: Steam flow in = Condensate flow out

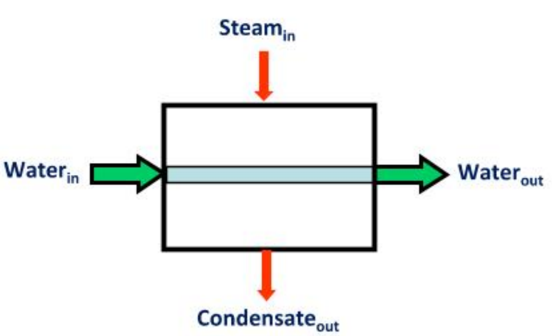
Conservation of Energy



Steady State Steady Flow

- Law: Energy can neither be created nor destroyed in the control volume. It can only be changed from one form to another.
- Mathematically,
  - Energy flow in + Heat = Energy flow out + Work
- Equation format
  - $\Sigma M_{in} * h_{in} + Q = \Sigma M_{out} * h_{out} + W$

Example: F1



- Water inlet temperature = 25°C
- Water outlet temperature = 75°C
- Specific heat of water = 4.183 kJ/kg-K
- Heat transferred to water
  $= M_{water} * Cp * (T_{out} - T_{in})$

$$Q = \frac{600}{60} \times 4.183 \times (75 - 25)\ kW$$
$$Q = 2{,}091\ kW$$

Example: F1

- Steam inlet conditions: Saturated steam at atmospheric pressure
- Condensate outlet conditions: Saturated at T = 100°C
- Heat transferred by steam = $M_{steam} * h_{steam} - M_{condensate} * h_{condensate}$
- No shaft work is done in the control volume: W = 0
- Heat transferred **to** water = Heat transferred **by** steam
- Conservation of Mass: $M_{steam} = M_{condensate}$

Example: F1

- $Q = M_{steam} * (h_{steam} - h_{condensate})$
- Steam Property tables provide information on steam and condensate enthalpies
- h_{steam} - Saturated steam (0 barg) = 2,676 kJ/kg
- $h_{condensate}$ - Sat. Condensate at 100°C = 419 kJ/kg

$$Q \quad = \mathrm{M}_{\mathrm{steam}} \times (2{,}676 - 419)$$
$$2{,}091 = \mathrm{M}_{\mathrm{steam}} \times (2{,}257)$$
$$\mathrm{M}_{\mathrm{steam}} = 0.927\ kg/s = 3{,}336\ kg/h = 3.34\ \mathrm{Tph}$$

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Example: F1

Pressure [bars]	t_{sat} [°C]	Quality	Enthalpy [kJ/kg]
0.5	81.3	0	340.4
0.5	81.3	1	2,645
1.013	100.0	0	419
1.013	100.0	1	2,676
1.5	111.4	0	467.1
1.5	111.4	1	2,693
2	120.2	0	504.7
2	120.2	1	2,707
2.5	127.4	0	535.4
2.5	127.4	1	2,717

Saturated Liquid

Saturated Vapor (Dry Steam)

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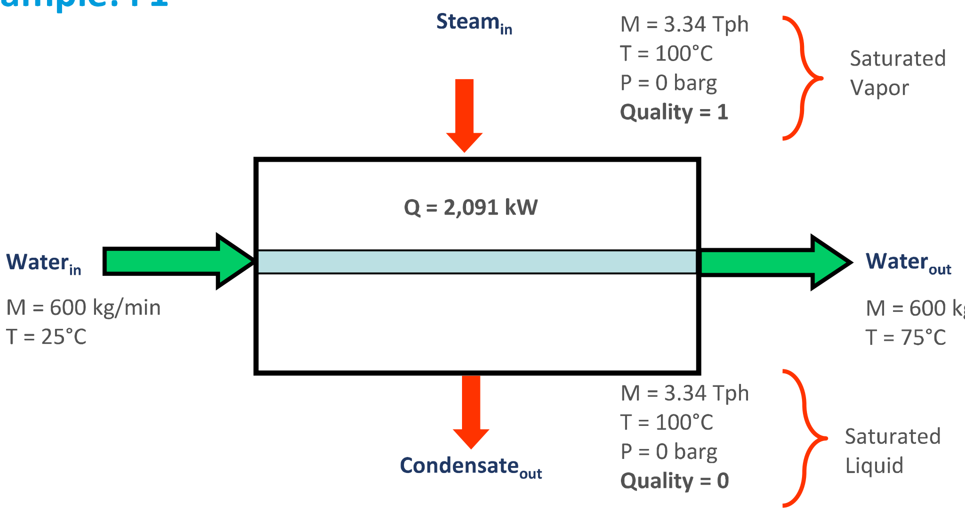
Example: F1



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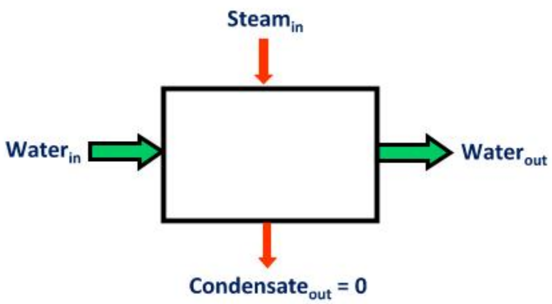
Example: F2



- Steam is directly injected in a vessel to heat water
- Water flow rate required (& measured) by process is 600 litres/min
- Steam flow rate is unknown

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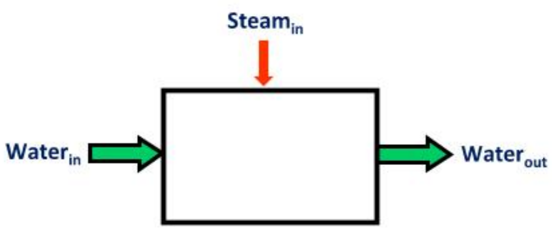
Example: F2

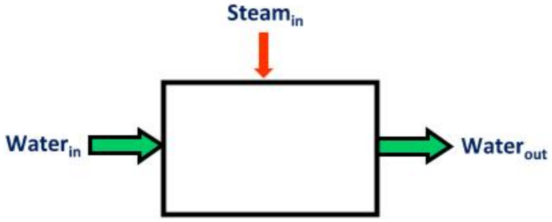


- Apply Steady State Steady Flow – **Conservation of Mass**
- Water flow in + Steam flow in = Water flow out

Example: F2

- Apply Steady State Steady Flow – Conservation of **Mass**
- Water flow in = $M_{waterin}$ = unknown
  Steam flow in = M_{steam} = unknown
- Water flow out = $M_{\ waterout}$
  = 600 litres/min
  ~ 600 kg/min
- $M_{waterin} + M_{steam} = M_{waterout}$ ...Eqn 1

Example: F2



- Water inlet temperature = 25°C
- Water outlet temperature = 75°C
- Steam inlet conditions: Saturated steam at atmospheric pressure
- No shaft work is done in the control volume: W = 0
- Apply Steady State Steady Flow - Conservation of **Energy**

$$M_{waterin} * h_{waterin} + M_{steam} * h_{steam} = M_{waterout} * h_{waterout} \quad \text{...Eqn 2}$$

Example: F2

Pressure$_i$ [bar]	Temperature$_i$ [°C]	Quality$_i$	Enthalpy$_i$ [kJ/kg]	Density$_i$ [kg/m3]
1.013	25.0	-100	104.8	997.1
1.013	75.0	-100	314	974.9
1.013	100.0	1	2,676	0.597

- Steam Property tables provide information on steam and sub-cooled water enthalpies
- $h_{waterin}$ - Subcooled water (25°C) = 104.8 kJ/kg
- h_{steam} - Saturated steam at 0 barg = 2,676 kJ/kg
- $h_{waterout}$ - Subcooled water (75°C) = 314 kJ/kg

Example: F2

- Equation 1 is now written as

$$M_{waterin} + M_{steam} = M_{waterout}$$

$$M_{waterin} + M_{steam} = \frac{600}{60} \times \frac{974.9}{1,000}$$

$$M_{waterin} + M_{steam} = 9.75$$

$$M_{waterout} = 9.75 \frac{kg}{s}$$

Example: F2

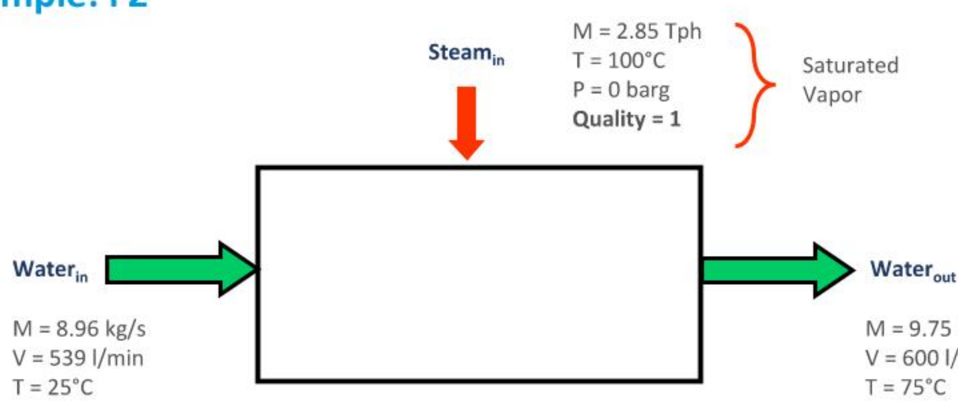
- Equation 2 can now be written as

$$
\begin{aligned}
M_{waterin} \times (104.8) + M_{steam} \times (2{,}676) &= M_{waterout} \times (314) \\
M_{waterin} \times (104.8) + M_{steam} \times (2{,}676) &= 9.75 \times (314) \\
M_{waterin} \times (104.8) + M_{steam} \times (2{,}676) &= 3{,}061.5
\end{aligned}
$$

- Equation 2 can now be written as

$$
\begin{aligned}
M_{waterin} &= 8.96\frac{kg}{s} = \frac{8.96}{997.1} \times 1{,}000 \times 60\frac{1}{min} = 539\frac{litres}{min} \\
M_{steam} &= 0.793\frac{kg}{s} = 2{,}855\frac{kg}{h} = 2.85\ Tph
\end{aligned}
$$

Example: F2

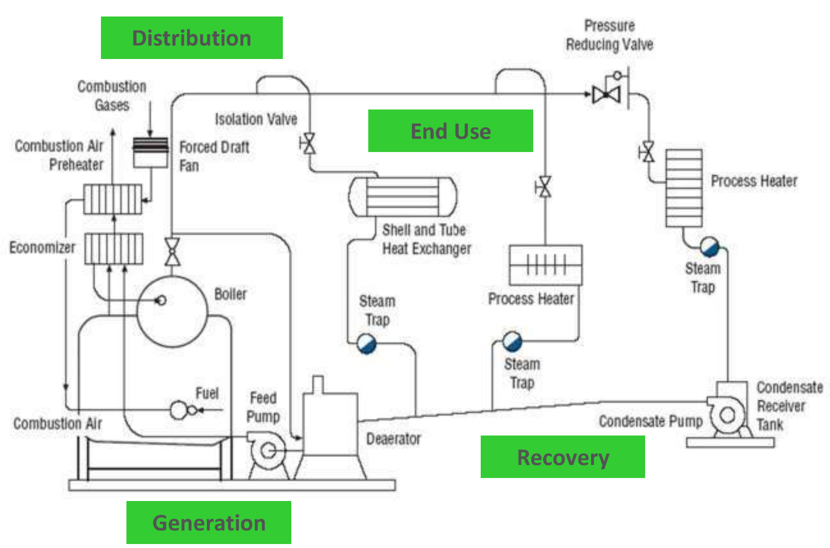


Key Points / Action Items

1. Use a Systems Approach to optimize steam systems
2. There are four major areas of a steam system – Generation, Distribution, End-Use & Recovery
3. An understanding of the laws of thermodynamics, heat transfer, fluid flow and steam properties is required for a steam system analysis
4. Steam is used all across the industry to do various tasks and is the most effective medium to transport energy and produce shaft work (or power)

Section 2: Steam System Scoping Tool:

- Steam System Optimization Opportunities
- Steam System Scoping Tool (SSST)
- Hands-On Exercise on SSST



Generic Steam System

Source: US DOE BestPractices Steam System Sourcebook

Common BestPractices - Generation

- Minimize excess air
- Install heat recovery equipment
- Clean boiler heat transfer surfaces
- Improve water treatment to reduce boiler blowdown
- Recover energy from boiler blowdown
- Add/restore boiler refractory
- Minimize the number of operating boilers
- Optimize deaerator vent rate

Source: US DOE BestPractices Steam System Sourcebook

Common BestPractices - Distribution

- Repair steam leaks
- Minimize vented steam
- Ensure that steam system piping, valves, fittings and vessels are well insulated
- Isolate steam from unused lines
- Minimize flows through pressure reducing stations
- Reduce pressure drop in headers
- Drain condensate from steam headers

Source: US DOE BestPractices Steam System Sourcebook

Common BestPractices – End-Use

- Reduce steam usage by a process
  - Improving the efficiency of the process
  - Shifting steam demand to a waste heat source
- Reduce the steam pressure needed by process, especially in cogeneration systems
- Upgrade low pressure (or waste) steam to supply process demands
- Process integration leading to overall energy optimization of the plant

Source: US DOE BestPractices Steam System Sourcebook

Common BestPractices - Recovery

- Implement an effective steam-trap management and maintenance program
- Recover as much as possible of available condensate
- Recover condensate at the highest possible thermal energy
- Flash high-pressure condensate to make low-pressure steam

Source: US DOE BestPractices Steam System Sourcebook

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Industrial Steam System Management Objective:

Minimize Steam Use, Energy Losses, GHG Emissions

Most Importantly
ENHANCE RELIABILITY OF OPERATIONS &
REDUCE STEAM SYSTEM OPERATING COSTS!!

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US Steam Market Assessment Takeaways

- Fuel savings estimates – individual projects – ranged from 0.6 percent to 5.2 percent
- Estimated payback periods generally very attractive
  - Ranged from 2 to 34 months
  - Most less than 2 years
- Potential steam savings in target industries – over 12 percent of fuel use

Promising Areas To Achieve Steam Energy and Cost Savings?

Use the US DOE Steam System Scoping Tool (SSST) For Initial Assessment

The SSST is available in both IP and SI units

US DOE Steam System Scoping Tool - SSST

- SSST is a software-based questionnaire designed to enhance awareness of areas of steam system management
- Divided into typical steam system focus areas
- Provides the user a score that is indicative of management intensity and serves as a guide to useful information
- Tool to identify potential improvement opportunity areas
- Will NOT quantify the energy savings opportunities

Intended SSST Users

- Industrial manufacturers
  - Plant managers
  - Utility managers
  - Plant process engineers
- Can also be used by institutional, commercial steam users

Two SSST Formats Available

- Excel Spreadsheet (Version 1.0d)
  - Linking capability across plants
  - Spreadsheet – Look and Feel
  - Manual entry of scores
  - SI / Metric version available

SSST Organization

- Introduction
- Steam system basic data
- Steam system profiling
- Overall system operating practices
- Boiler plant operating practices
- Distribution, end use and recovery operating practices
- Summary results
- Next steps

Obtaining Data for SSST Input

- Sources of data:
  - Actual current measurements
  - Computerized or print copy historical records
  - Information on procedures from:
    - Plant engineer/utilities/maintenance manager(s)
    - Boiler operator
- 26 questions – expected time: 30 min (max)

Steps for Use of SSST

- Load program
- Open SSST by clicking on opening title screen
- Review SSST sections to identify needed input data
- Obtain input data
- Optionally complete steam system basic data section
- Insert answer choices into SSST sections

Steps for Use of SSST (cont.)

- On summary results screen note scores achieved in major sections
- Compare scores achieved with those for similar plants
- Identify and prioritize steam system improvement opportunities
- Utilize resources identified in "next steps" section for assistance in implementing steam system improvements

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SSST Scorecard – Results

- What is the condition of your system?
- Allows for identifying potential improvement opportunities and focus areas

SUMMARY OF RESULTS SCOPING TOOL AREAS	POSSIBLE SCORE	TYPICAL SCORE
STEAM SYSTEM PROFILING	90	63%
STEAM SYSTEM OPERATING PRACTICES	140	69%
BOILER PLANT OPERATING PRACTICES	80	63%
DISTRIBUTION, END USE, RECOVERY OP. PRACTICES	30	58%
TOTAL SCOPING TOOL QUESTIONAIRE SCORE	340	222.0
TOTAL SCOPING TOOL QUESTIONAIRE SCORE	100%	65%

Source: US DOE Steam BestPractices Program

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Interpreting Summary Results

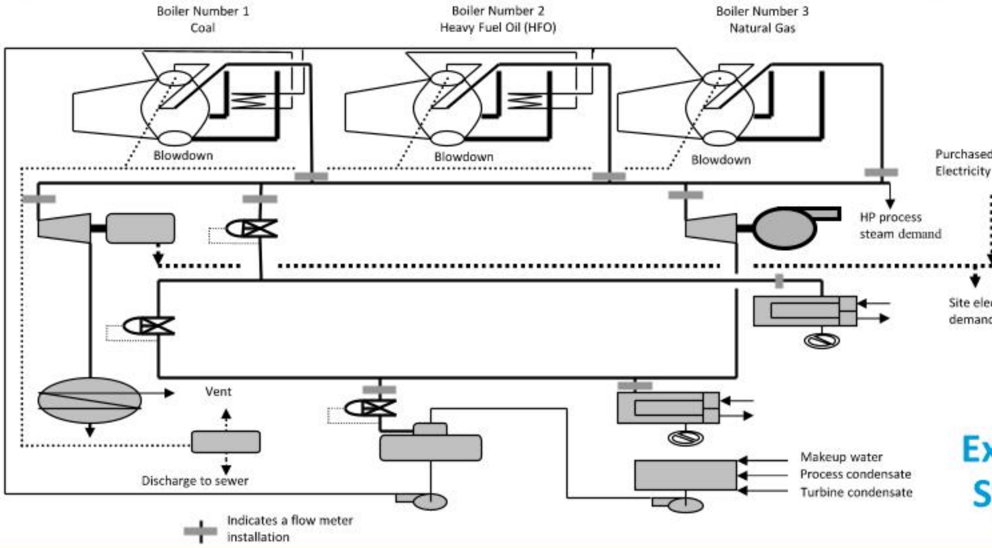
- Total possible score: 340 points
- Average scores reported with results from over 150+ energy assessments:
  - Steam system profiling: 62%
  - Total steam system operating practices: 69%
  - Boiler plant operating practices: 62%
  - Steam distribution, end use and heat recovery practices: 58%
  - Overall average score reported: 65%

Interpreting Scores

- Notable variation in category scores
  - Best performance in category of total steam system operating practices (69%)
  - Poorest performance in category of steam distribution, end use and heat recovery practices (58%)
  - Modest scores overall indicate substantial opportunity for steam system improvement
  - SSST can be used to trend improvements

SSST Hands-On Exercise

- You have been tasked with a steam system assessment at a pulp and paper mill
- The plant Utilities Manager & Utilities Engineer are available to provide information to you about the plant
- Open SSST and input available plant data
- Identify missing data and determine appropriate plant source for this data
- List possible steam system improvement opportunities that you would like to investigate



Example System

SSST Hands-On Exercise (cont.)

- The plant (and steam system) operates 24 hours/day, 365 days/year;
- There are three boilers: Coal-fired, HFO-fired and Natural gas-fired
- The coal-fired and HFO-fired boilers are operated at base-load (fixed) whereas the Natural gas boiler responds to load variations
- Typical average loads correspond to ~65-70% of total available capacity
- Boiler instrumentation is limited to header pressure and boiler steam output

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SSST Hands-On Exercise (cont.)

- Monthly boiler fuel (coal, HFO and Natural gas) costs are tracked but not related to steam or product production rates
- Boiler combustion efficiency is measured on a semi-annual basis using portable instrumentation
- Fireside heat transfer surfaces are normally found to be clean
- Waterside surfaces have had to be cleaned about every three years
- A feedwater economizer exists on the coal-fired and the HFO boiler

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SSST Hands-On Exercise (cont.)

- Blowdown for all boilers is done manually by the operators based on TDS and conductivity measurements taken once during the day
- An outside contractor provides boiler water treatment services based on monthly visits to the plant
- There are have been no problems with the regulation of boiler pressure, water levels or steam quality

SSST Hands-On Exercise (cont.)

- There is uncertainty about the number of steam traps in the plant; traps have not been surveyed for some time due to reduction in maintenance staff; but traps are checked and repaired/replaced if production is affected
- Steam system components are inspected and serviced as needed only when process operators report problems
- Condensate recovery averages 50% based on make-up water amounts

SSST Hands-On Exercise (cont.)

- During a walk-through inspection of the plant the following observations were made:
  - Within the utilities areas, most of the steam distribution piping and system components seemed well insulated
  - There were several lengths of steam pipe and valves with modest amounts of missing insulation in the rest of the plant
- No evidence of water hammer was detected
- No leak management program at the plant and several minor steam leaks are observed

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SSST Hands-on Exercise Instructions

- For the plant information presented, provide data input to the SSST and arrive at scores for each SSST section and the summary listing
- For all questions for which input data is unavailable or insufficient, specify how you would obtain the needed information during your plant visit
- Based on your SSST analysis results, develop a list of priority actions to achieve energy conservation in the example plant

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SSST Hands-on Exercise Results

SUMMARY OF STEAM SCOPING TOOL RESULTS

	POSSIBLE SCORE	YOUR SCORE
STEAM SYSTEM PROFILING	90	36
STEAM SYSTEM OPERATING PRACTICES	140	70
BOILER PLANT OPERATING PRACTICES	80	49
DISTRIBUTION, END USE, RECOVERY OP. PRACTICES	30	22
TOTAL SCOPING TOOL QUESTIONAIRE SCORE	340	177
TOTAL SCOPING TOOL QUESTIONAIRE SCORE (%)		52.1%
Date That You Completed This Questionaire		6/6/2011

SSST Hands-on Exercise Results

SCOPING TOOL QUESTIONS	POSSIBLE SCORE	YOUR SCORE
1. STEAM SYSTEM PROFILING		
STEAM COSTS		
SC1: Measure Fuel Cost To Generate Steam	10	5
SC2: Trend Fuel Cost To Generate Steam	10	5
STEAM/PRODUCT BENCHMARKS		
BM1: Measure Steam/Product Benchmarks	10	0
BM2: Trend Steam/Product Benchmarks	10	0
STEAM SYSTEM MEASUREMENTS		
MS1: Measure/Record Steam System Critical Energy Parameters	30	21
MS2: Intensity Of Measuring Steam Flows	20	5
STEAM SYSTEM PROFILING SCORE	90	36

SSST Hands-on Exercise Results

2. STEAM SYSTEM OPERATING PRACTICES		
STEAM TRAP MAINTENANCE		
ST1: Steam Trap Maintenance Practices	40	8
WATER TREATMENT PROGRAM		
WT1: Water Treatment - Ensuring Function	10	5
WT2: Cleaning Boiler Fireside/Waterside Deposits	10	5
WT3: Measuring Boiler TDS, Top/Bottom Blowdown Rates	10	5
SYSTEM INSULATION		
IN1: Insulation - Boiler Plant	10	10
IN2: Insulation - Distribution/End Use/Recovery	20	14
STEAM LEAKS		
LK1: Steam Leaks - Severity	10	8
WATER HAMMER		
WH1: Water Hammer - How Often	10	10
MAINTAINING EFFECTIVE STEAM SYSTEM OPERATIONS		
MN1: Inspecting Important Steam Plant Equipment	20	5
STEAM SYSTEM OPERATING PRACTICES SCORE	140	70

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SSST Hands-on Exercise Results

3. BOILER PLANT OPERATING PRACTICES		
BOILER EFFICIENCY		
BE1: Measuring Boiler Efficiency - How Often	10	5 ←
BE2: Flue Gas Temperature, O2, CO Measurement	15	9
BE3: Controlling Boiler Excess Air	10	7
HEAT RECOVERY EQUIPMENT		
HR1: Boiler Heat Recovery Equipment	15	3 ←
GENERATING DRY STEAM		
DS1: Checking Boiler Steam Quality	10	10
GENERAL BOILER OPERATION		
GB1: Automatic Boiler Blowdown Control	5	0 ←
GB2: Frequency Of Boiler High/Low Level Alarms	10	10
GB3: Frequency Of Boiler Steam Pressure Fluctuations	5	5
BOILER PLANT OPERATING PRACTICES SCORE	80	49

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SSST Hands-on Exercise Results

4. STEAM DISTRIBUTION, END USE, RECOVERY OPERATING PRACTICES		
MINIMIZE STEAM FLOW THROUGH PRVs		
PR1: Options For Reducing Steam Pressure	10	10
RECOVER AND UTILIZE AVAILABLE CONDENSATE		
CR1: Recovering And Utilizing Available Condensate	10	6 ←
USE HIGH-PRESSURE CONDENSATE TO MAKE LOW-PRESSURE STEAM		
FS1: Recovering And Utilizing Available Flash Steam	10	6 ←
DISTRIBUTION, END USE, RECOVERY OP. PRACTICES SCORE	30	22

SSST Hands-on Exercise Next Steps

- Steam system profiling
  - Calculate steam costs & trend
  - Correlate steam costs with production and benchmark
- Steam System Operating Practices
  - Incorporate Steam Trap Management Program
  - Investigate steam system insulation in the plant
  - Investigate causes for water-side fouling issues
  - Evaluate the need for periodic inspection of steam system equipment

SSST Hands-on Exercise Next Steps

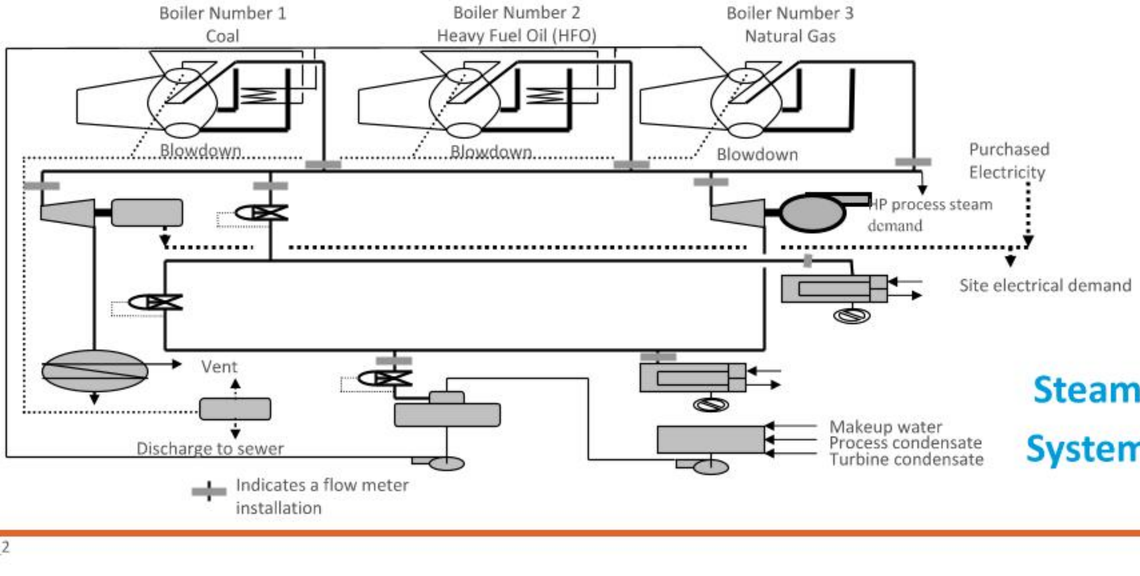
- Boiler Plant Operating Practices
  - Calculate and trend individual boiler and overall plant steam generation efficiency & trend
  - Investigate excess air control equipment and in-situ measuring equipment
  - Investigate feedwater economizer
  - Investigate blowdown thermal energy recovery
  - Improve boiler blowdown control
- Distribution, End-Use & Recovery
  - Back-pressure turbine optimization
  - Improve condensate return & flash steam recovery

Key Points / Action Items

1. Use a systematic approach (gap analysis, comparison to BestPractices) to identify potential energy saving opportunities that may exist in steam systems
2. The US DOE's Steam System Scoping Tool (SSST) can be used to identify these improvement opportunities
3. It is available "free"
4. The SSST can also be used as an intake questionnaire to collect preliminary plant level information
5. It contains 26 questions and shouldn't take more than 30 minutes to complete

Section 3: US DOE MEASUR Tool (MEASUR):

- Overview of US DOE MEASUR
- MEASUR Calculators
- MEASUR Assessments
- Impact Utility Costs
- Boiler Efficiency
- 3-header Student Hands-On Exercise



Steam System

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US DOE MEASUR Tool

- MEASUR Tool
  - **M**anufacturing **E**nergy **A**ssessment **S**oftware for **U**tility **R**eduction
  - Its in Beta phase because US DOE is constantly adding new features continuously
- Download free from the US DOE website – MEASUR
  - https://www.energy.gov/eere/amo/measur
  - Search for US DOE MEASUR on the internet
  - Download and install – creates a shortcut on the desktop
  - Checks for updates automatically and let's you download the updated version so that you have the latest version available every time you run it

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US DOE MEASUR Tool

- *MEASUR Tool*
  - Now available ONLINE also!
  - Launched in August 2022
  - https://measur.ornl.gov
- Everything should be identical to the downloaded version
- Some additional testing and checking is ongoing

US DOE MEASUR Tool (cont.)

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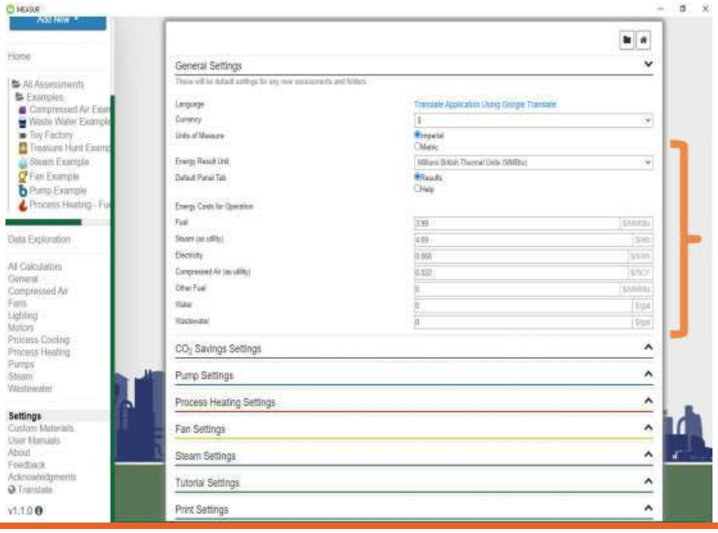

Settings

- The first place to be visited
- Sets all the unit defaults, costs, if information is available

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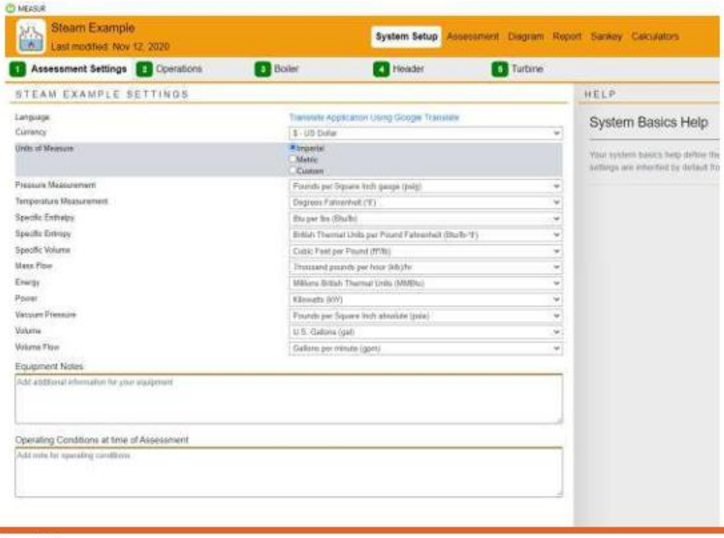
US DOE MEASUR Preferences



- Full flexibility is offered to the user to select default (IP) or choose Custom units for the parameters
- Generally, US$ is the easiest currency to work with but some other currencies are available
- HELP is always around

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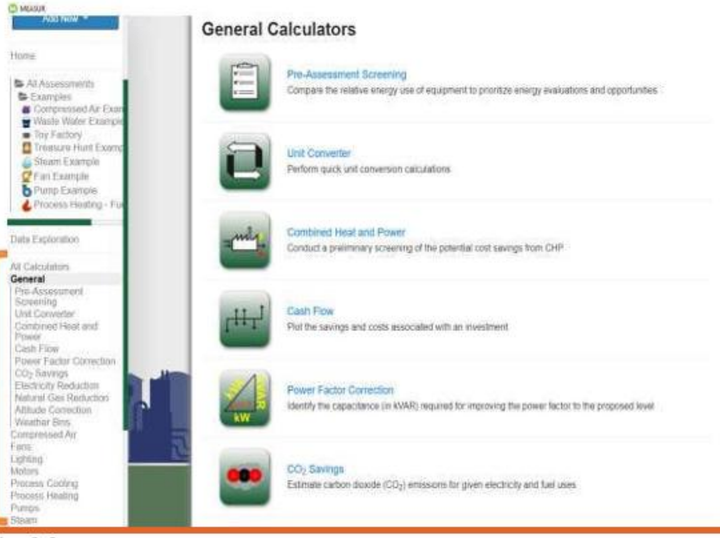
All Calculators



- MEASUR has several calculators
- General calculators are cross-cutting and NOT system specific

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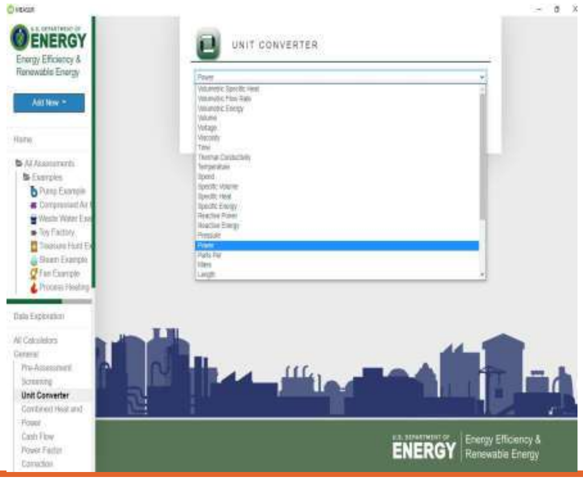
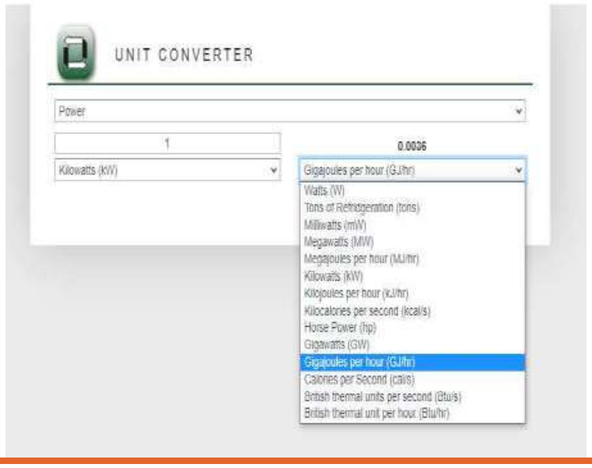
General Calculators – Unit Converter





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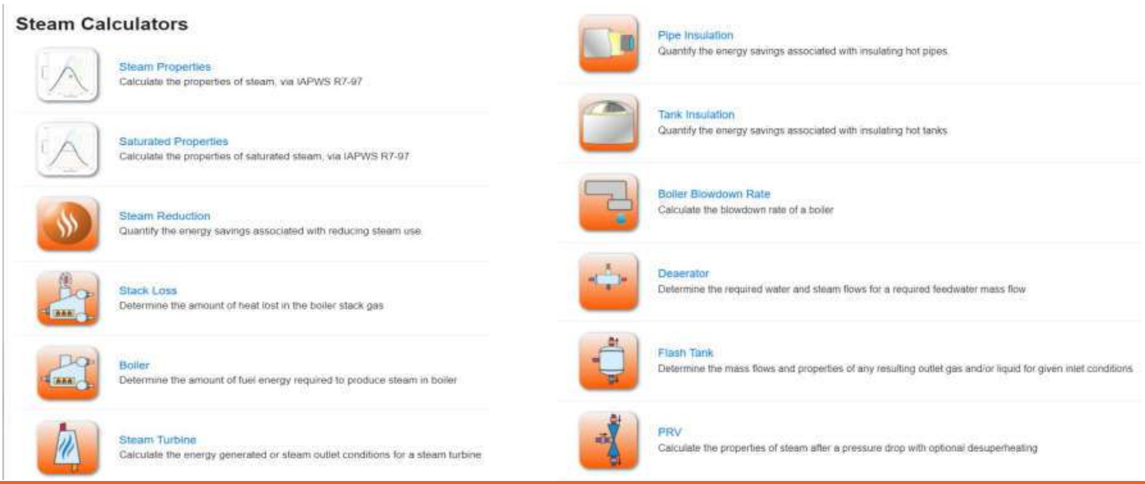
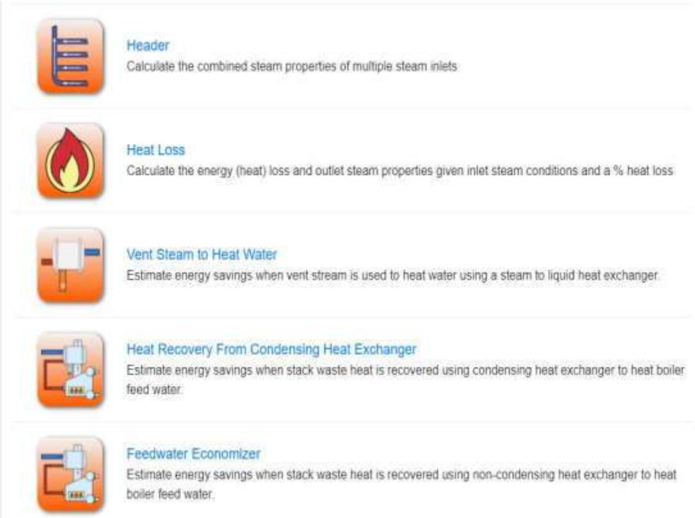
Steam Calculators

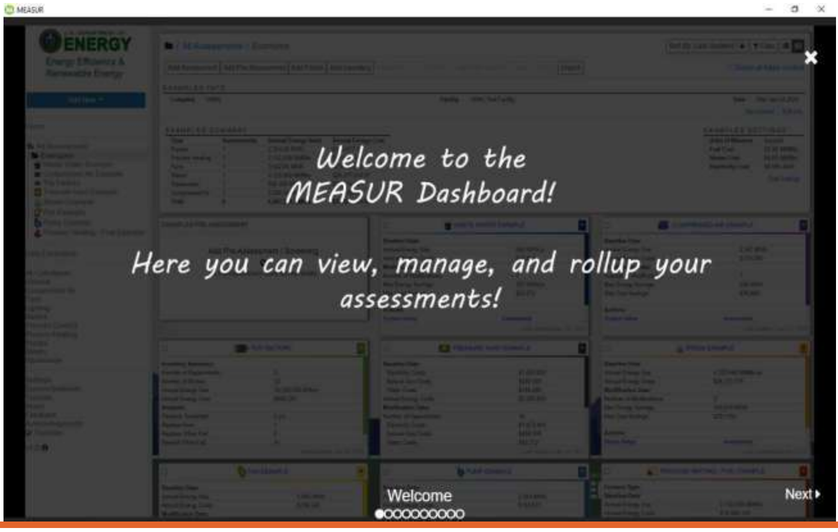




Steam Calculators

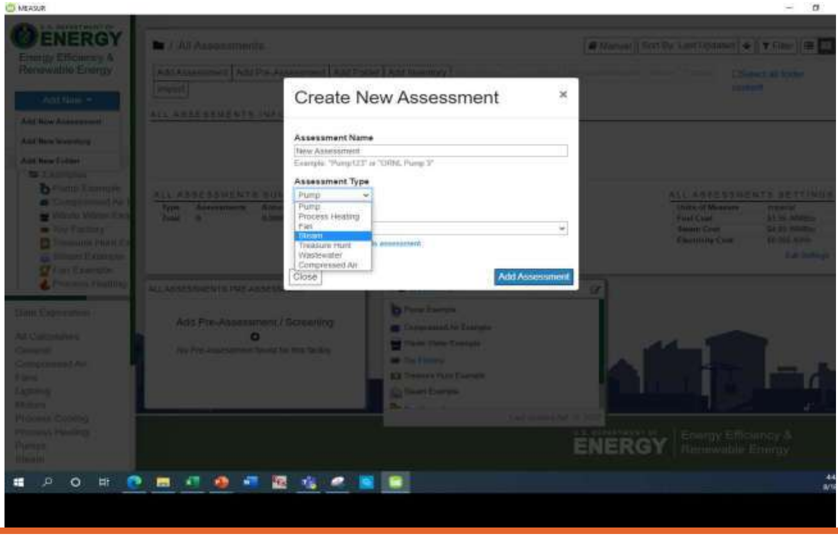
- These calculators provide a quick analysis
- 1st level Quantification

Pumping System Calculators



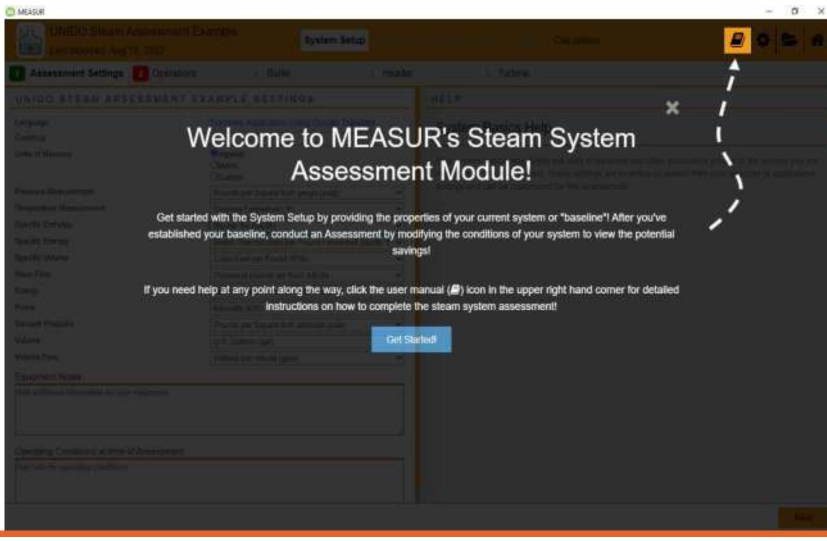
MEASUR Dashboard

Section_3_13

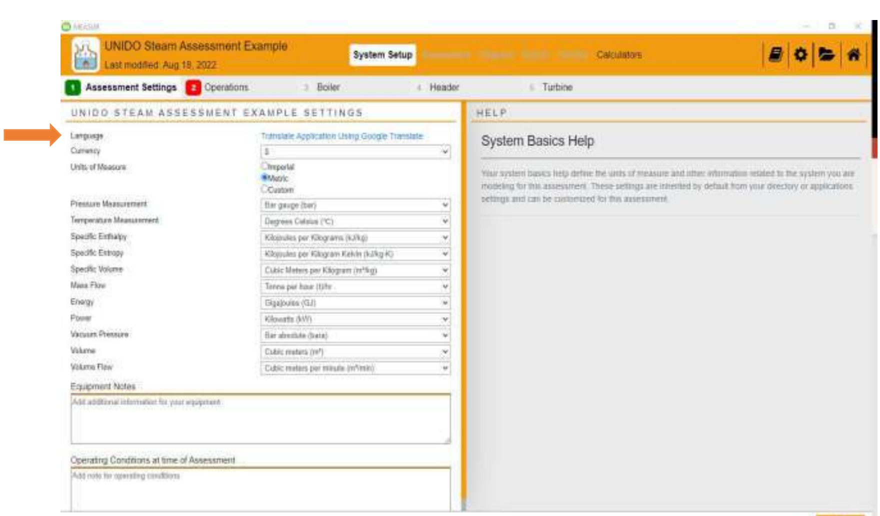


MEASUR's - Assessment Module

Section_3_14

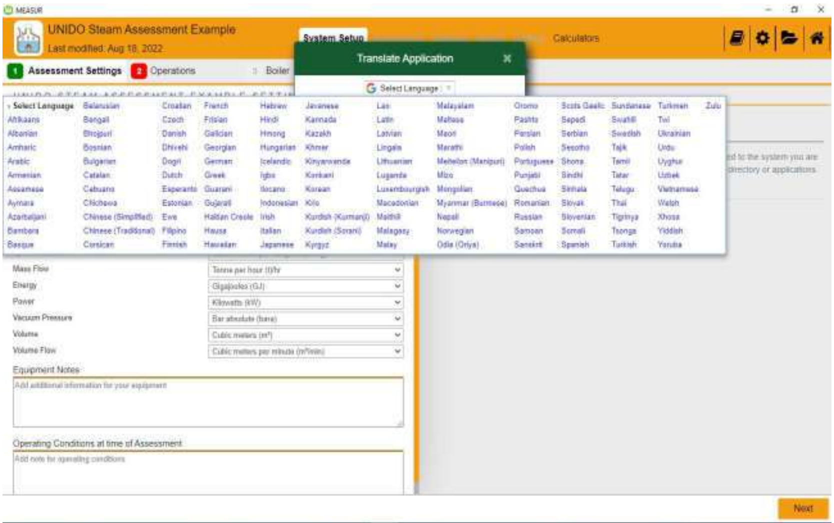


MEASUR's Steam Assessment Module

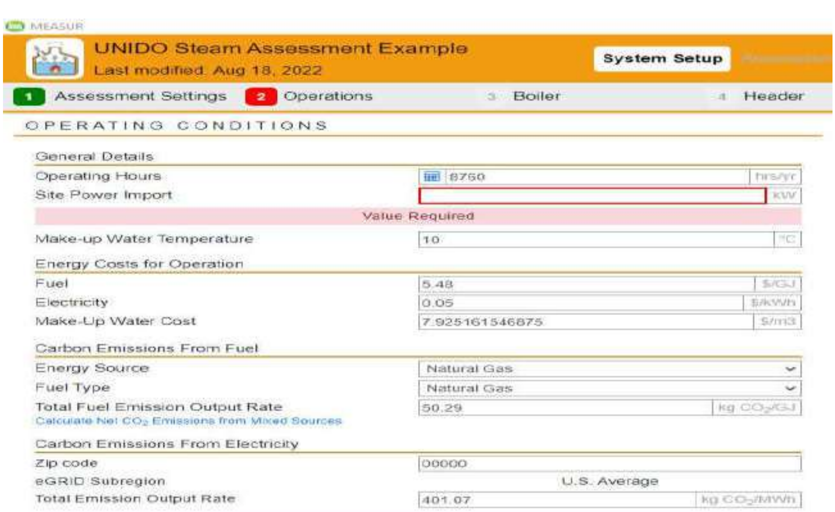


Input Sections – Assessment Settings

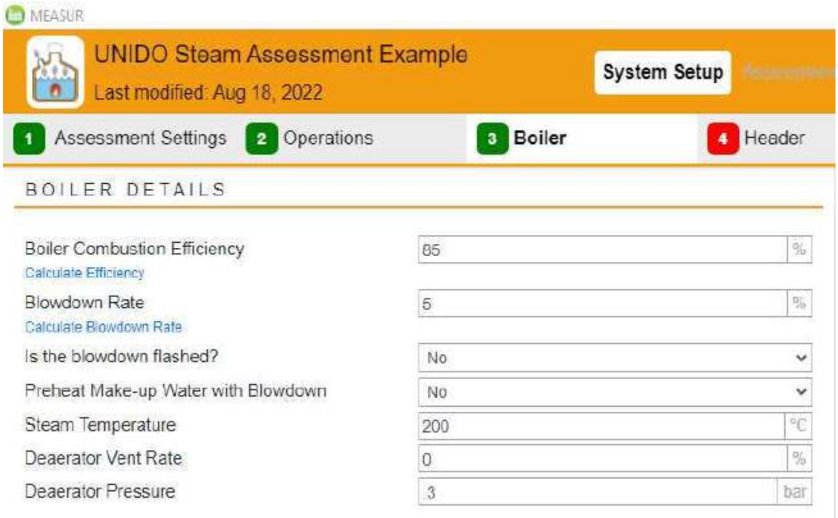
Input Sections – Assessment Settings (cont.)



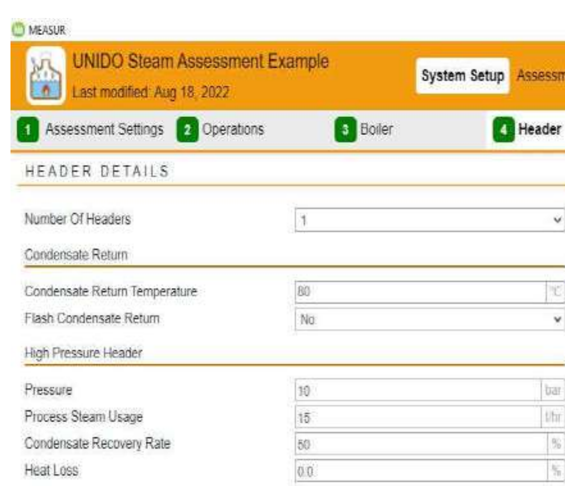
Input Sections – Operations



Input Sections – Boiler



Input Sections – Header



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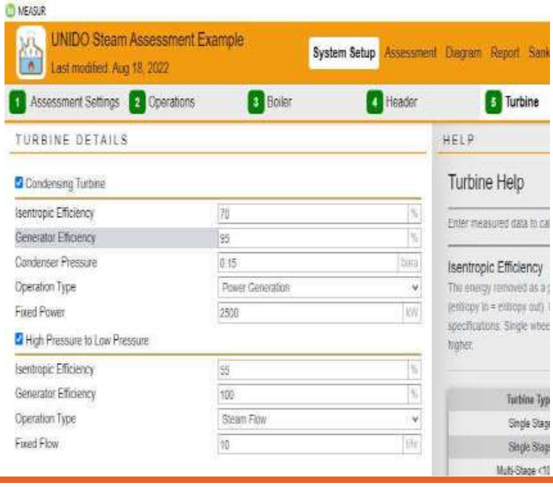
Input Sections – Turbine



Turbine Type	Exhaust Type	Average (%)
Single Stage	Back Pressure	53
Single Stage	Condensing	57
Multi-Stage <10MW	Back Pressure	60
Multi-Stage <10MW	Condensing	67
Multi-Stage >10MW	Back Pressure	75
Multi-Stage >10MW	Condensing	80

Source: https://www.elliott-turbo.com/TurbineCalculator

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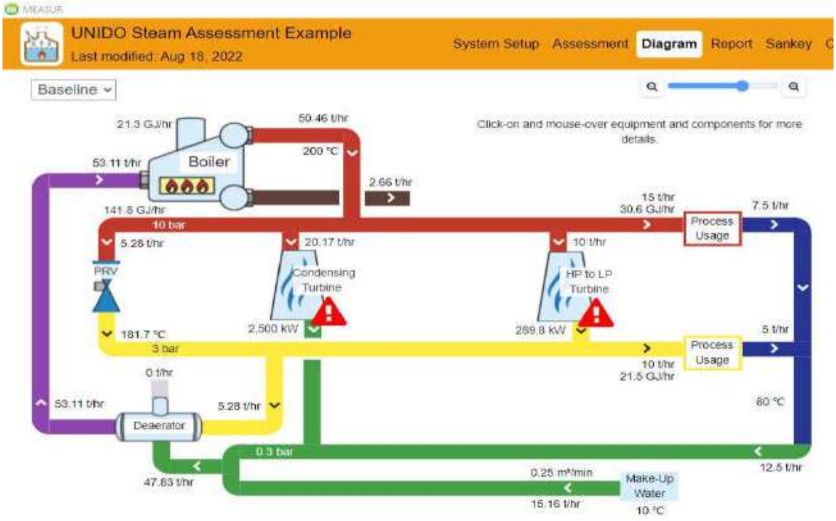


Steam System Diagram

Steam System Summary

RESULTS | HELP

STEAM SYSTEM SUMMARY

Steam Generated	
50.5 t/hr	
Total Operating Cost	
$10,050,894	

CO_2 Emissions (tonne CO_2/yr)	
Emissions From Fuel	62,480.81
Emissions From Selling Electricity	0
Emissions From Change in Electricity Imports	0
Total Emissions	62,480.81

Fuel	
Boiler Fuel Use	1,242,410.19 GJ/yr
Boiler Fuel Cost ($)	$6,808,408

Electricity	
Electricity Generated	2,789.79 kW
Electricity Imported	5,000 kW
Electricity Cost ($)	$2,190,000

Make-Up Water	
Make-Up Water Required	132,803.12 m³
Make-up Water Cost ($)	$1,052,486

COST SUMMARY

Power Balance	
Generation	2,789.8 kW
Demand	7,789.8 kW
Import	5,000 kW
Unit Cost	$0.05 /kWh
Total $/yr	$2,190,000

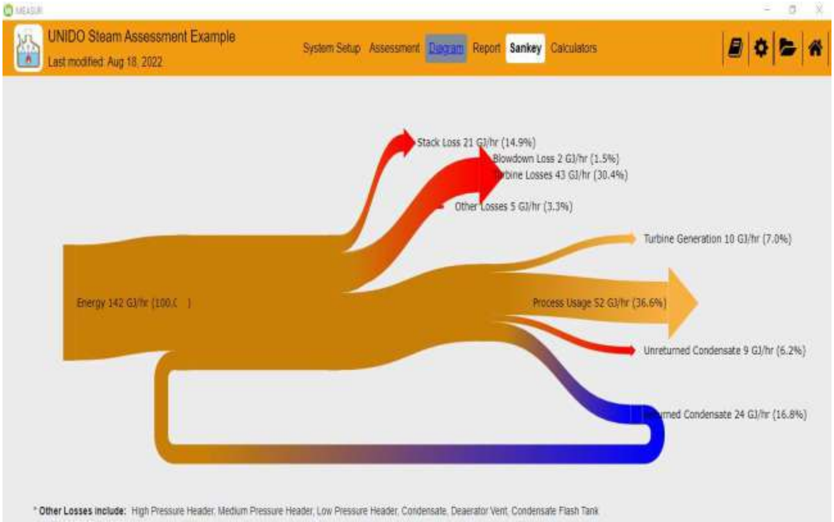
Fuel Balance	
Boiler	141.83 GJ/hr
Unit Cost	$5.48 /GJ
Total $/yr	$6,808,408

Make-Up Water	
Flow	0.25 m³/min 132,803.12 m³
Unit Cost	$7.9252 /m³
Total $/yr	$1,052,486

Total Operating Cost
$10,050,894

MARGINAL STEAM COST

High Pressure	$21.71 /t
Medium Pressure	$0.00 /t
Low Pressure	$21.68 /t



Steam System Sankey Plot

Key Features of MEASUR (Steam Model)

- Choice of 1, 2, or 3 Header Pressure Models
- Schematics of Model Steam Systems
- Energy & Cost Summaries
- Estimates of Environmental Emissions

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Key Features of MEASUR (Steam Model)

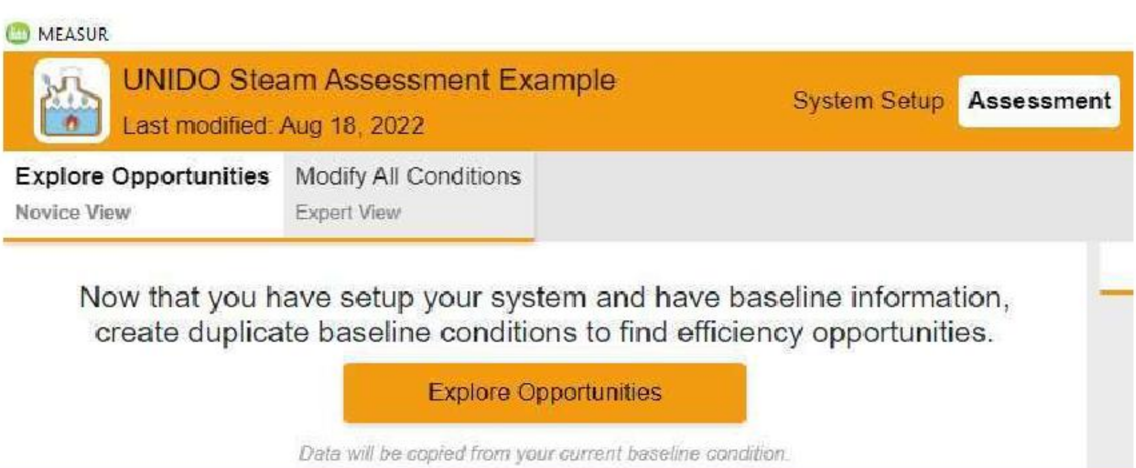
- Major Equipment Simulated:
  - Boiler(s)
  - End-uses
  - Back-pressure turbines
  - Condensing turbine
  - Deaerator
  - Insulation losses
  - Letdowns
  - Flash vessels
  - Heat recovery exchangers

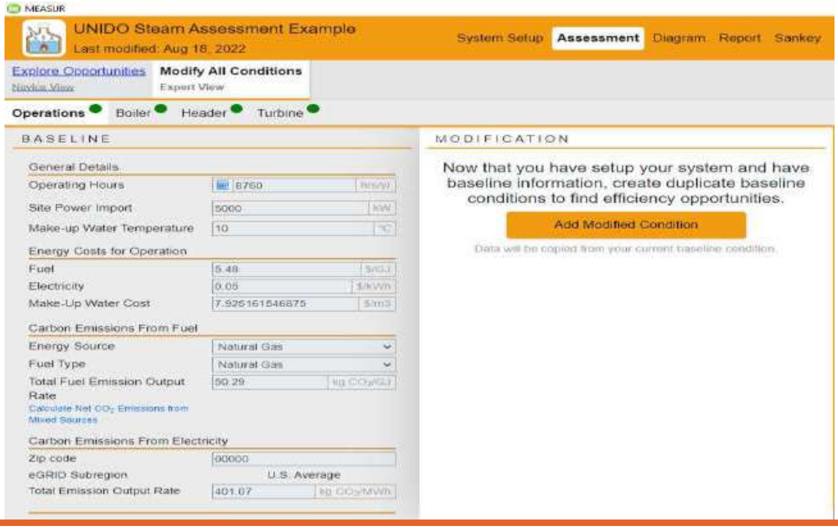
The MEASUR Steam Assessment Can Evaluate Key Steam Improvement Projects

- Steam Demand Changes
- Boiler Efficiency
- Alternative Fuels
- Steam Turbines
- Boiler Blowdown Energy Recovery
- Condensate Recovery
- Heat Recovery
- Flash Steam Recovery

…. And many more project scenarios

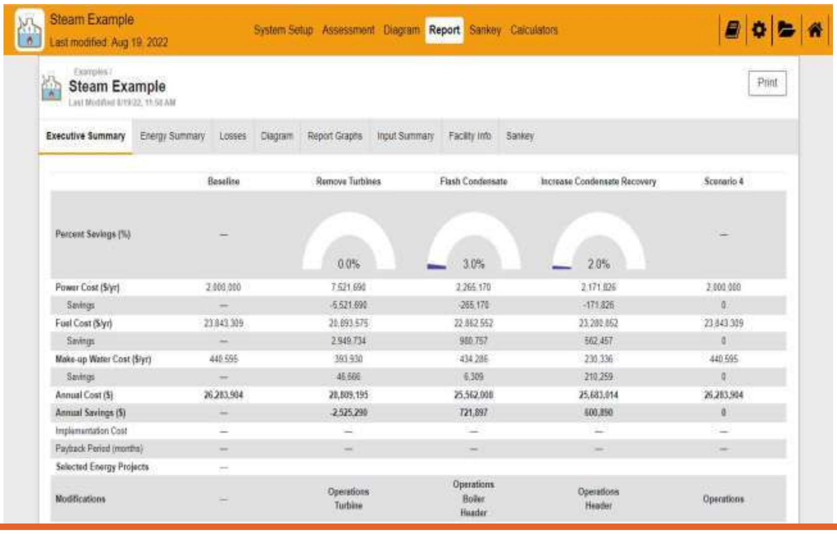
Assessment Page (Novice View)





Assessment Page (Expert View)

Section_3_29



Report (Executive Summary)

Section_3_30

US DOE MEASUR

- Start MEASUR
  - Installed version
  - Online version
- Start at “Settings” tab
  - General settings
  - Steam system settings
- Open two MEASUR windows on the browser
  - Steam system assessment
  - Calculators

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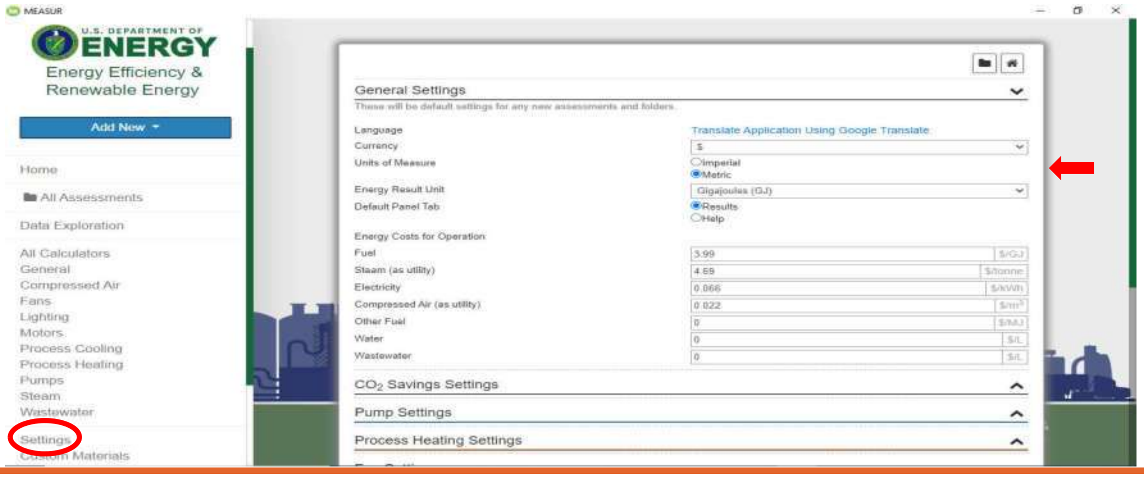
MEASUR (Overall System Settings)



MEASUR (Steam System Assessment)

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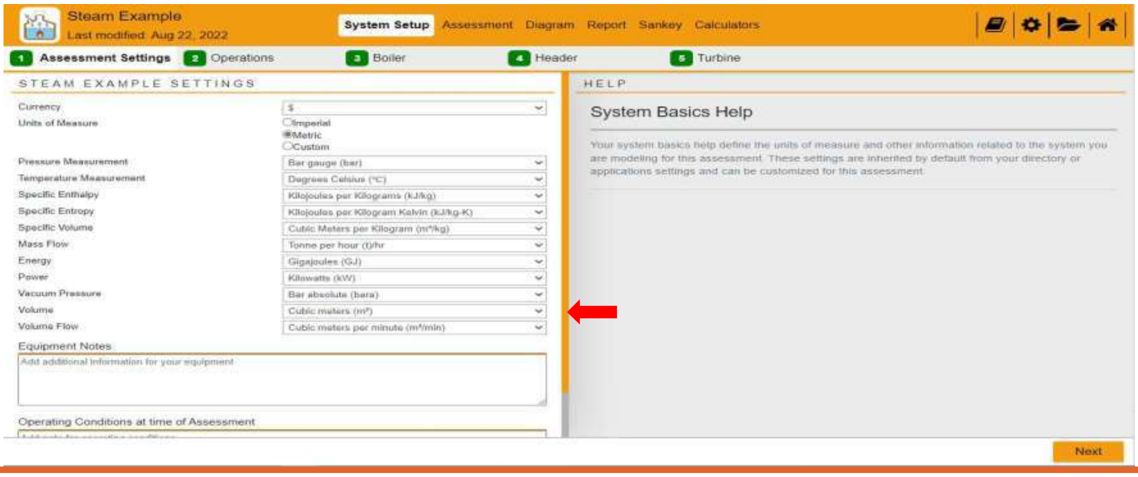
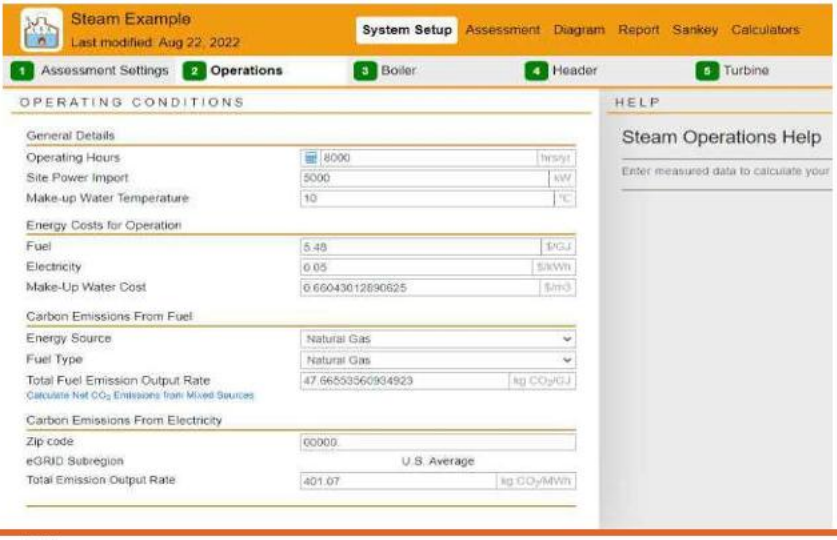
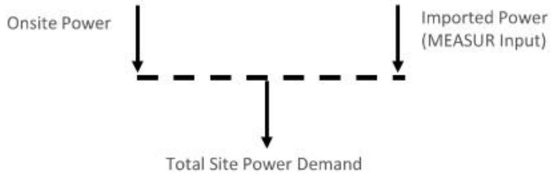
MEASUR (Steam System Settings)





MEASUR (Steam System Operations)

Site Power Import (or Export)



- MEASUR requires an input for the normal amount of import electrical power
- Import electrical power combined with site generated power is the site load
- If the site is a net exporter of power a negative value should be provided for the import power

Electric Rate Structure

- A thorough understanding of the electric rate structure is essential to evaluate the true impact of any process change
- The average electric cost is generally not the unit cost a facility will be impacted by as a result of an increase or decrease in electrical consumption
- Fixed costs should NOT be included in MEASUR impact-type analysis

Electric Utility Costs

- 1st Level of Information
  - Annual electric utility bill: $4,860,000
  - Annual electrical energy consumption: 43,800 MWh
- Electric utility cost can be calculated as follows

$$ElectricCost = \frac{4{,}860{,}000}{43{,}800{,}000} = 0.111 \frac{\$}{kWh}$$

- But this cost may be INCORRECT for use in MEASUR analysis

Electric Utility Costs

- 2nd Level of Information
  - Annual electric utility bill: $4,860,000
  - Annual electrical energy consumption: 43,800 MWh
  - Fixed Charges: $480,000
- Reducing energy consumption will NOT change the fixed charges and hence, they shouldn't be included in MEASUR
- Electric utility cost can be calculated as follows

$$ElectricCost = \frac{(4{,}860{,}000 - 480{,}000)}{43{,}800{,}000} = 0.10\frac{\$}{kWh}$$

- This cost may be CORRECT for use in MEASUR analysis, if Electric Demand is going to be impacted

Electric Utility Costs

- 3rd Level of Information
  - Annual electric utility bill: $4,860,000
  - Annual electrical energy consumption: 43,800 MWh
  - Fixed Charges: $480,000
  - Annual Demand charges: $876,000
  - Annual Energy charges: $3,504,000
- If electric Demand is NOT impacted then Demand charges should NOT be included in MEASUR
- Electric utility cost can be calculated as follows

$$ElectricCost = \frac{(4{,}860{,}000 - 480{,}000 - 876{,}000)}{43{,}800{,}000} = 0.08\frac{\$}{kWh}$$

Electric Utility Costs

- Different configuration
  - Demand charge: $14.60 per kW per month
  - Energy charge: $0.08 per kWh
- MEASUR has only one cell ($/kWh) for input

$$\boldsymbol{\kappa}_{energy} = 0.080\,\frac{\$}{kWh}$$

$$\boldsymbol{\kappa}_{demand} = 14.6\,\frac{\$}{kW\ month}\left(\frac{1\ month}{730\ hrs}\right) = 0.020\,\frac{\$}{kWh}$$

$$ElectricCost = \boldsymbol{\kappa}_{energy} + \boldsymbol{\kappa}_{demand} = 0.10\,\frac{\$}{kWh}$$

Makeup Water Costs

- Water purchase price
- Pumping costs
- Treatment costs
- Wastewater costs ???
- Makeup water temperature is an important variable
- Use 20°C for example steam system
- A typical cost is $0.66/m^3

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MEASUR Fuel Selection

- Steam & Hot water
  - Doesn't really apply unless directly importing stream from another plant
- Natural gas
- Petroleum-based fuels
  - Diesel (#2 fuel oil)
  - LPG
  - Other hydrocarbons, etc
- Biomass fuels
  - Biodiesel
  - Bagasse
  - Wood, etc
- Natural gas
  - Different grades
- Other fuels
  - Coke
  - Hydrogen, etc
- Mixed fuel (user-defined)

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Fuel Heating Value

- The energy content of a fuel is determined by a combustion process
  - The combustion process begins and ends at ambient temperature
  - The energy released during the combustion process is measured
    - Heat of Combustion for the fuel (calorific value and the *heating value)*
- Fuels containing hydrogen will form water during combustion

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Energy Release}$$

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Higher Heating Value (HHV)

- Water (H_2O) formed during the combustion process is initially steam but condenses during the heating value test
  - Each kg of water releases ~2,325 kJ of energy by condensing
    - This energy release is measured in the **Higher Heating Value**
  - In the United States, HHV is the common convention
    - The primary exception is the combustion turbine arena

$$CH_4 + 2O_2 \rightarrow CO_2 + \underbrace{2H_2O}_{condensate} + \text{Energy Release}$$

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Lower Heating Value (LHV)

- The Lower Heating Value is the energy liberated from a combustion process with no latent energy release from condensation
- The Lower Heating Value is generally determined by calculation from the higher heating value and the fuel composition
- In most boiler operations the flue gas will exit the boiler with no condensate
- The Lower Heating Value is the convention in most of the world

$$CH_4 + 2O_2 \rightarrow CO_2 + \underbrace{2H_2O}_{Steam} + \text{Energy Release}$$

Higher and Lower Heating Value

- The numeric difference between the higher and lower heating values depends on the hydrogen content of the fuel
  - Natural gas (Natural gas) difference is 10%
  - Fuel oil difference is 6%
  - Coal difference is ~4%
  - Green wood difference can be more than 20%
- In the United States most fuels are marketed based on the fuel higher heating value
- The primary point of concern is consistency

Fuel Cost Structure – Impact Fuel

- Analyses should be completed utilizing impact costs
- Gross indications of savings opportunities can be attained by use of average impact cost or projected cost
- Multiple models may need to be developed reflecting various pricing conditions
  - Fuel prices typically vary seasonally
- When the site fuel is not an MEASUR fuel the most similar MEASUR fuel should be used
  - The MEASUR fuel cost should equal the actual energy related fuel cost

Fuel Selection

- How should multi-fuel sites be modeled?
  - Impact fuel cost should be utilized
    - The fuel that will change consumption if steam demand changes
    - Typically, highest cost fuel in use but NOT always
    - "Blended costs" generally do not reflect actual system changes
      - Blended costs **do** provide a confidence level in the model results

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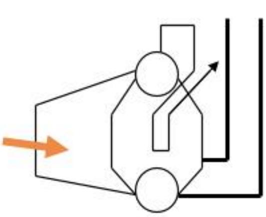
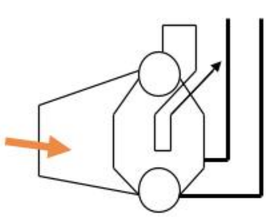
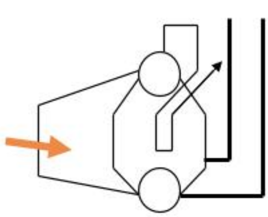


Fuel: Coal
Fuel cost: $170/tonne
Boiler capacity: 90 Tph
Steam production: 65 Tph
Boiler efficiency: 85%



Fuel: Heavy Fuel Oil
Fuel cost: $785/tonne
Boiler capacity: 90 Tph
Steam production: 65 Tph
Boiler efficiency: 84%

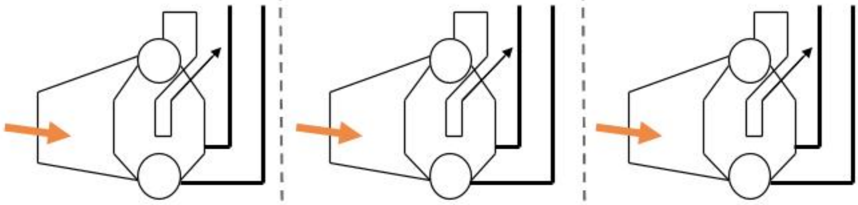


Fuel: Natural gas
Fuel cost: $1.0/Nm^3
Boiler capacity: 30 Tph
Steam production: 20 Tph
Boiler efficiency: 80%

Fuel Selection

- Turndown issues limit minimum fire operation
- Maximum fire issues limit continuous output
- **What is the impact fuel in this operation?**

Fuel Selection



Fuel: Coal
Fuel cost: $5.4/GJ
Boiler capacity: 90 Tph
Steam production: **65 Tph**
Boiler efficiency: 85%

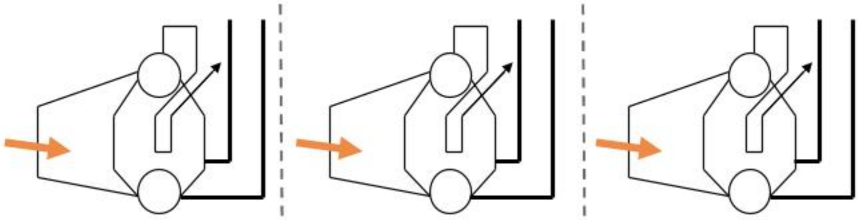
Fuel: Heavy Fuel Oil
Fuel cost: $18/GJ
Boiler capacity: 90 Tph
Steam production: **65 Tph**
Boiler efficiency: 84%

Fuel: Natural gas
Fuel cost: $25/GJ
Boiler capacity: 30 Tph
Steam production: **20 Tph**
Boiler efficiency: 80%

- From a pure cost perspective – Natural gas fired boiler is the impact boiler
  - **It has the highest steam production cost!**

Average Fuel Cost

Steam conditions:
25 bars and 375°C



Fuel: Coal
Fuel cost: $5.4/GJ
Boiler capacity: 90 Tph
Steam production: **65 Tph**
Boiler efficiency: 85%

Fuel: Heavy Fuel Oil
Fuel cost: $18/GJ
Boiler capacity: 90 Tph
Steam production: **65 Tph**
Boiler efficiency: 84%

Fuel: Natural gas
Fuel cost: $25/GJ
Boiler capacity: 30 Tph
Steam production: **20 Tph**
Boiler efficiency: 80%

- **For this operating condition the "average fuel cost" is ~$13.6/GJ**
- **Combined boiler plant efficiency is 83.9%**
- This is good to use to check overall utilities agreement

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Specifying Fuel & Cost in MEASUR

Fuel	Sales Unit	Typical Cost [$/sales unit]	HHV [kJ/kg]	Unit Price [$/GJ]
Natural Gas	Nm³	1.00	54,220	26.35
Number 2 Fuel Oil	tonne	1,500	45,125	33.24
Number 6 Oil (LS)	tonne	785	43,595	18.01
Number 6 Oil (HS)	tonne	797	43,764	18.21
Bituminous Coal	tonne	171	31,890	5.36
SubBituminous Coal	tonne	129	23,465	5.50
Green Wood	tonne	22	12,215	1.80

This is VERY IMPORTANT. The units of fuel cost in MEASUR are based on ENERGY.

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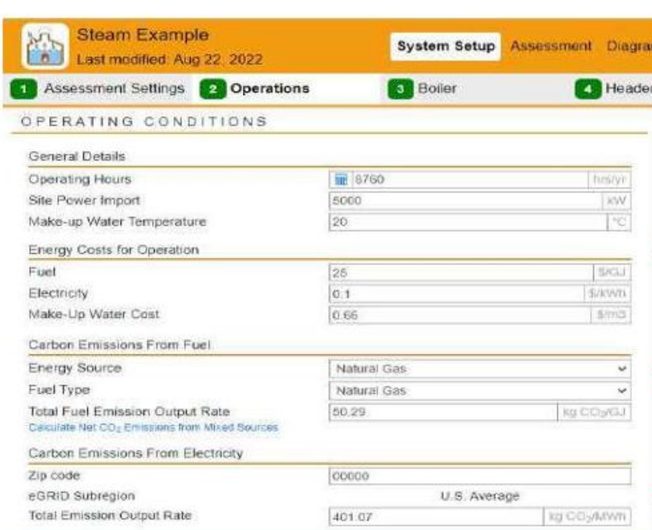

Specifying Impact Fuel & Cost in MEASUR

- The Emissions information provides Scope 1 & 2
- Default emission factors from US database are provided OR use site & fuel-specific factors, if known

Steam Generation Cost for Natural Gas Boiler

- Boiler fired with Natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/Nm^3
- Steam generation: 20 Tph (all year round average)
- Fuel supply: 1,693 Nm^3/hr (28 Nm^3/min)
- Fuel cost: \$1.0/Nm^3
- Determine the operating cost?

$$K\_boiler = m\_fuel \times k\_fuel = 1{,}693 \times 1.0 = \$1{,}693/hr$$

$$K\_boiler = \$1{,}693/hr \times 8{,}760 \approx \$14{,}800{,}000/yr$$

Steam Generation Cost for Natural Gas Boiler

$$K\_boiler = mfuel \times kfuel = 1{,}693 \times 1.0 = \$1{,}693/hr$$

$$K\_boiler = \$1{,}693/hr \times 8{,}760 \approx \$14{,}800{,}000/yr$$

- Steam generation: 20 Tph (steady all year round)
- **Determine the steam cost?**

$$\kappa_{steam} = \frac{Boiler\ Operating\ Cost}{Steam\ Generation}$$

$$\kappa_{steam} = \frac{1{,}693}{20} = 84.6\ \frac{\$}{tonne}$$

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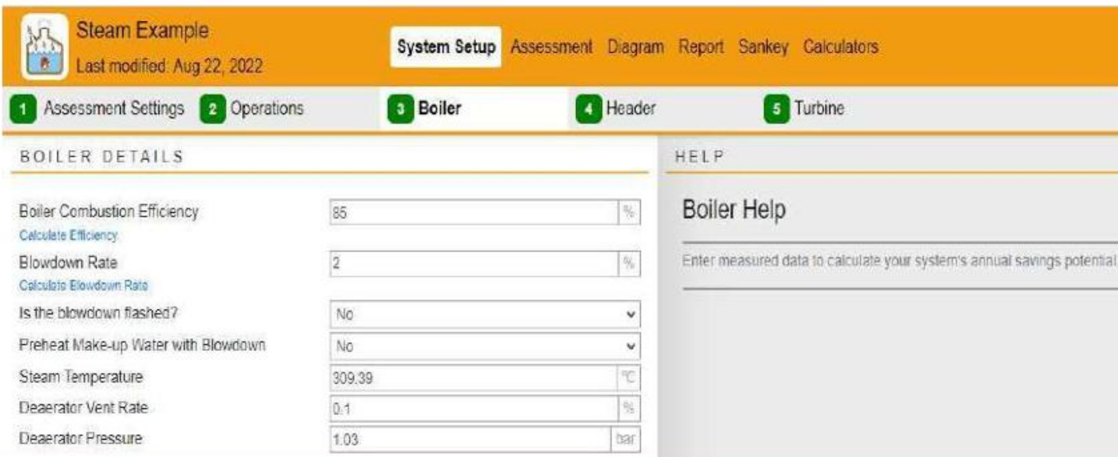
MEASUR Boiler Section



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ASME Boiler Efficiency

- American Society of Mechanical Engineers (ASME) has established a comprehensive testing standard for fired boilers
  - ASME Power Test Code 4 (ASME PTC–4)
    - Fuel efficiency (the same as the classic equation)
    - Gross efficiency (includes auxiliary input streams)
  - ASME PTC–4 describes two investigation methods
    - Input/output (direct method)
    - Energy balance (indirect method)

ASME – PTC 4 Determination of Boiler Efficiency

- Two generally accepted methods
  - Input-Output method

$$Efficiency = \frac{Output}{Input} \times 100$$

- Energy Balance method

$$Efficiency = \left[\frac{Input + Credits - Losses}{Input}\right] \times 100$$

$$Efficiency = \left[1 - \frac{(Losses - Credits)}{Input}\right] \times 100$$

- Primary difference between the methods lies in accuracy of measurements and identification of losses

Source: ASME PTC 4 – 2008; Section 3-1.3; Pages 19-20

Classic Boiler Efficiency

- Steam generating efficiency is defined as the heat absorbed by the steam divided by the energy input of the fuel

$$\eta_{boiler} = \frac{Energy\ absorbed\ by\ steam}{Fuel\ input\ energy} \times 100$$

$$\eta_{boiler} = \frac{m_{steam}\left(h_{steam} - h_{feedwater}\right)}{m_{fuel}\ HHV_{fuel}} \times 100$$

- This equation can be applied to a boiler or a boiler plant
- This equation can be applied for an instantaneous snapshot or any defined time-period (daily, month, annual, etc.)

Typical Boiler Efficiency

- A typical boiler will have an efficiency of ----?

75%	82%	87%
Wood	**Natural gas**	**Oil and Coal**

- Efficiency is dependent on several factors:
  - Type of fuel
  - Installed equipment and controls
  - Boiler load, etc.

Steam Generation Efficiency

- Boiler fired with Natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/m^3
- Steam generation: 20 Tph (steady all year round)
- Steam conditions: 25 bars, 375°C
- Boiler feedwater: 30 bars, 110°C
- Fuel supply: 1,693 Nm^3/hr (28 Nm^3/min)
- Fuel cost: \$1.0/Nm^3
- **Determine the boiler operating efficiency?**

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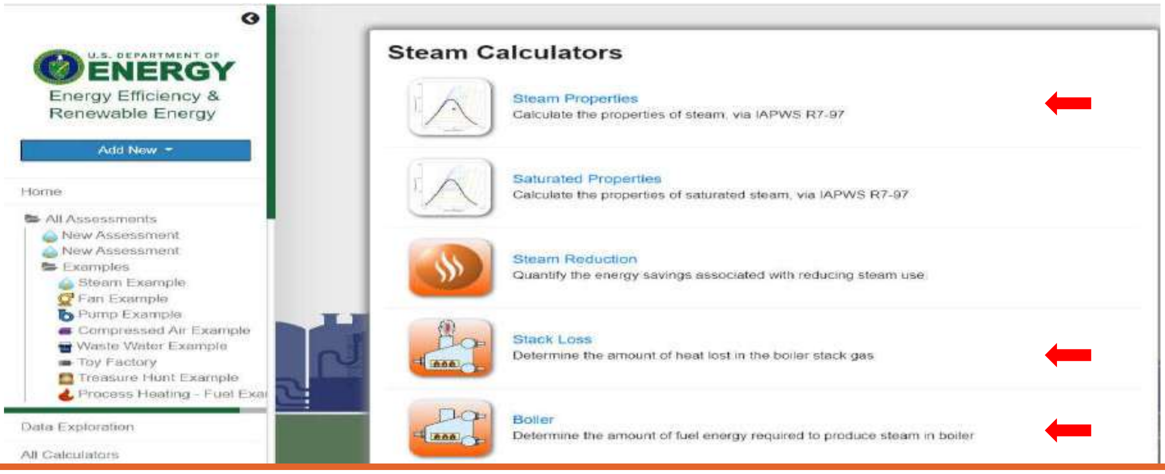
MEASUR Steam Calculators



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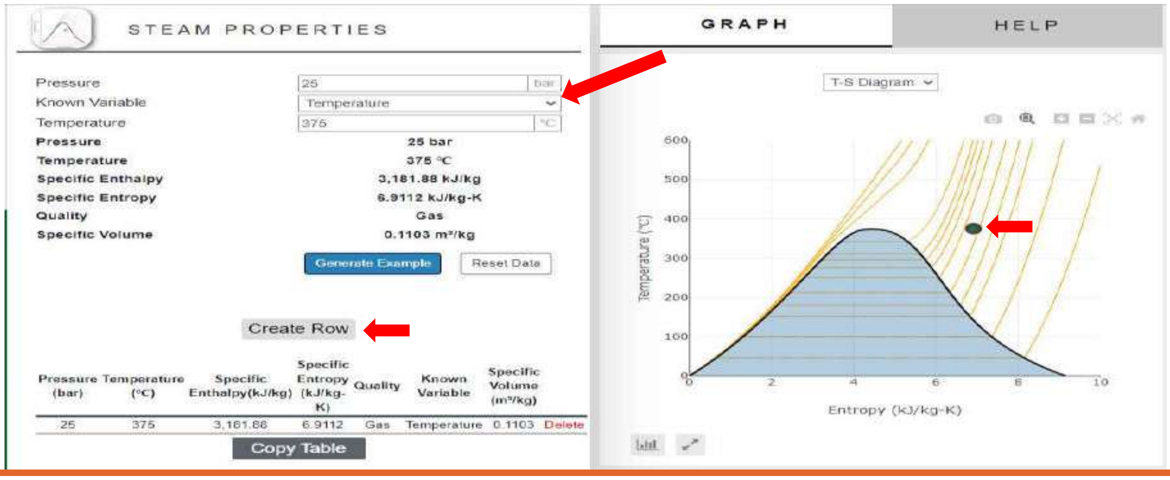
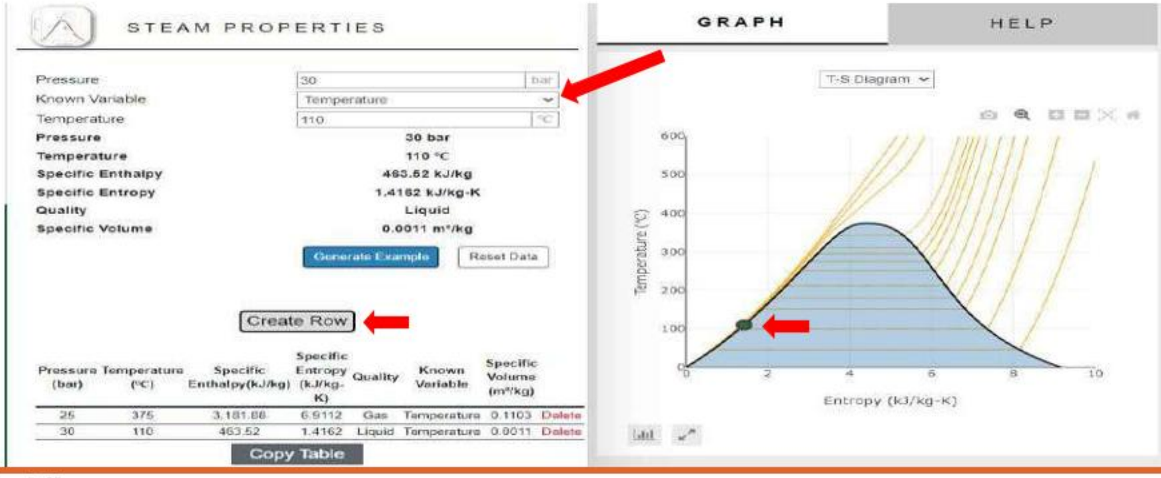
MEASUR Steam Calculators



MEASUR Steam Calculators



Steam Generation Efficiency

$$\eta_{boiler} = \frac{m_{steam}\left(h_{steam} - h_{feedwater}\right)}{m_{fuel}\, HHV_{fuel}} \times 100$$

- m_{steam} = 20,000 kg/hr
- h_{steam} = 3,181.9 kJ/kg
  - 25 bars, 375°C – superheated
- $h_{feedwater}$ = 463.5 kJ/kg
  - 30 bars, 110°C
- M_{fuel} = 1,693 m^3/hr
- HHV_{fuel} = 40,144 kJ/m^3

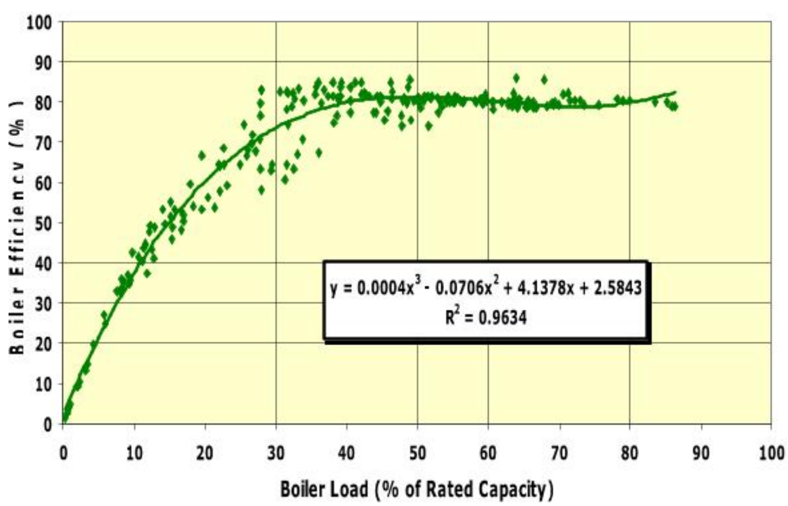
*Steam tables provide thermodynamic information for steam and feedwater

Steam Generation Efficiency

$$\eta_{boiler} = \frac{m_{steam}\left(h_{steam} - h_{feedwater}\right)}{m_{fuel}\,HHV_{fuel}} \times 100$$

$$\eta_{boiler} = \frac{\mathit{20{,}000}\,(3{,}181.9 - 463.5)}{\mathit{1{,}693} \times 40{,}144} \times 100$$

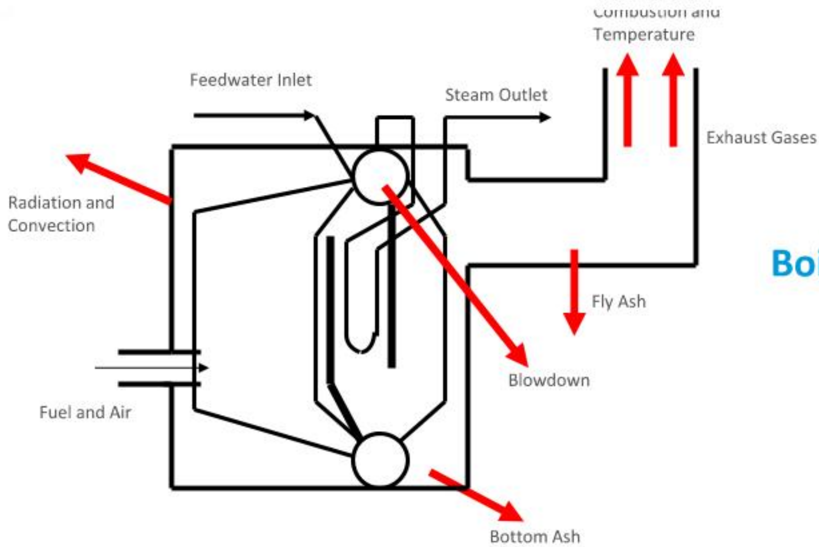
$$\eta_{boiler} = 80.0\%$$



Typical Boiler Efficiency Curve

- Why is the efficiency not 100%?

Boiler losses



Source: US DOE Steam BestPractices Program

- Boiler efficiency can also be determined in an indirect manner by determining the magnitude of the losses
  - Primary losses are typically
    - Shell loss
    - Blowdown loss
    - Stack loss

$$\eta_{boiler} = 100 - Losses$$

$$\boxed{0}$$

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

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Key Points / Action Items

1. Determine boiler plant operating cost
2. Determine unit cost of steam generation
3. Determine boiler operating efficiency

$$\eta_{boiler} = \frac{m_{steam}\left(h_{steam} - h_{feedwater}\right)}{m_{fuel}\, HHV_{fuel}} \times 100$$

4. There are three major losses in steam generation – shell loss, blowdown loss and stack loss

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

0

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Shell Loss Magnitude

- This is a very difficult number to evaluate accurately
- It has to be done with extensive field measurements and heat transfer calculations
- The American Society of Mechanical Engineers (ASME) Power Test Code 4 (PTC-4) identifies a calculation procedure to *estimate* boiler shell loss.
  - ASME PTC-4-2008, Section 5.14.9, pages 91-92.
- Typically, this is NOT a big loss compared to the other losses
- Can be estimated based on load using BestPractices data
- Nevertheless, can be a potential improvement opportunity

First Order Shell Loss Guide

Shell Loss Gross Estimate Field Evaluations				
Boiler Type	Steam Production Rating		Boiler Full-Load Shell Loss Estimate	
	Minimum [Tph]	Maximum [Tph]	Maximum [% fuel input energy]	Minimum [% fuel input energy]
Water-tube	5	50	2.0	0.3
Water-tube	50	500	0.6	0.1
Water-tube	500	5,000	0.2	0.1
Fire-tube	0.5	20	1.0	0.1

Source: US DOE Steam BestPractices Program

Example Boiler Shell Loss

- From an *ASME type* investigation the radiation and convection loss of the boilers is ~0.5% of the total fuel energy input to the boilers
- Total fuel energy cost ~$14,800,000 per year
- This represents a boiler shell loss of ~$74,000/yr for the Natural gas boiler
- Note: Actual monetary loss for each boiler will be different due to different fuel prices and boiler sizes

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Shell Losses

- Full-load radiation and convection losses are typically:
  - Less than 1.0% for water-tube boilers
  - Less than 0.5% for fire-tube boilers
- Shell loss *percentage* increases as boiler load decreases because shell loss magnitude is essentially constant
  - Shell loss of ~0.5% at full-load will become ~2.0% at quarter-load
  - The primary opportunity in this area is to reduce the number of boilers in operation to reduce the total site shell loss
    - Stack loss impacts must be considered
- Reducing steam demand will NOT result in any change in shell loss..... Unless a boiler is shut down!

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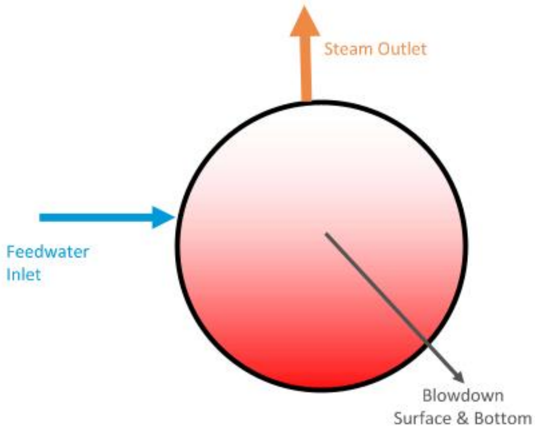
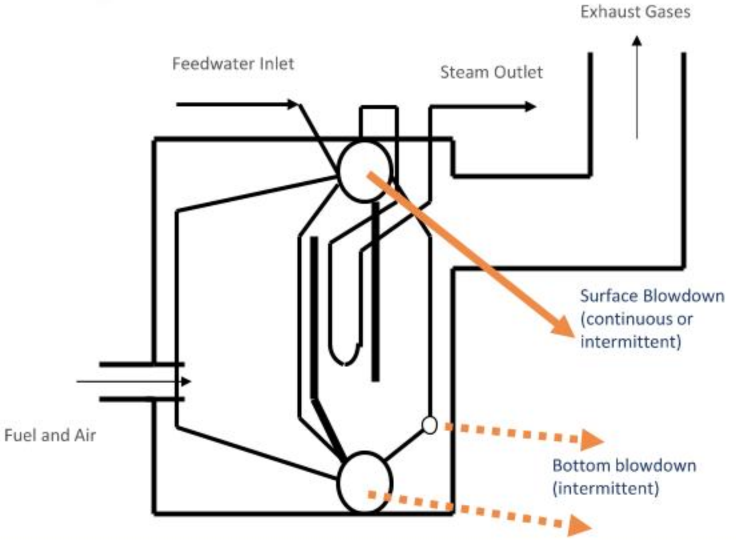


Blowdown Losses

- Boiler water contains dissolved minerals that are insoluble in steam
- These minerals do NOT leave with steam
- The concentration of these chemicals increases as time goes on
- Water is removed from the boiler to maintain proper water chemistry

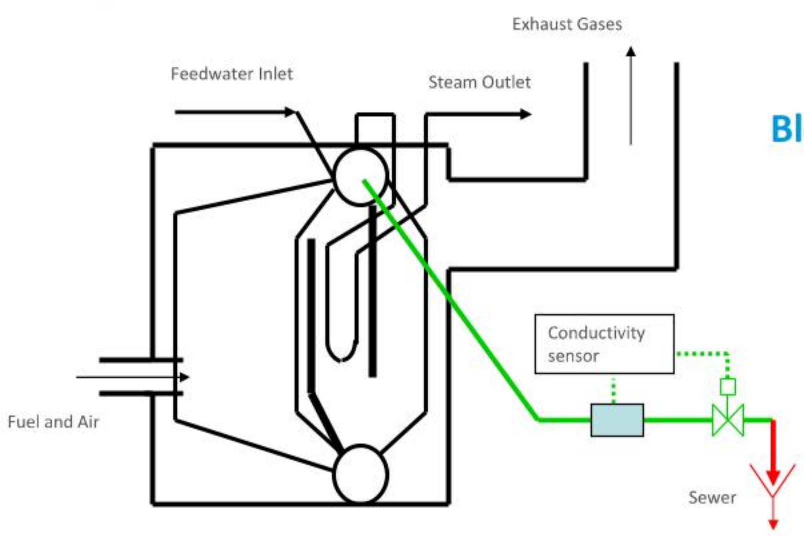
Boiler blowdown takes several forms



- Surface
  - Continuous
  - Intermittent
- Bottom
  - Intermittent

Source: US DOE Steam BestPractices Program

Blowdown Control



- Conductivity must be correlated to actual water quality through specific analysis

Source: US DOE Steam BestPractices Program

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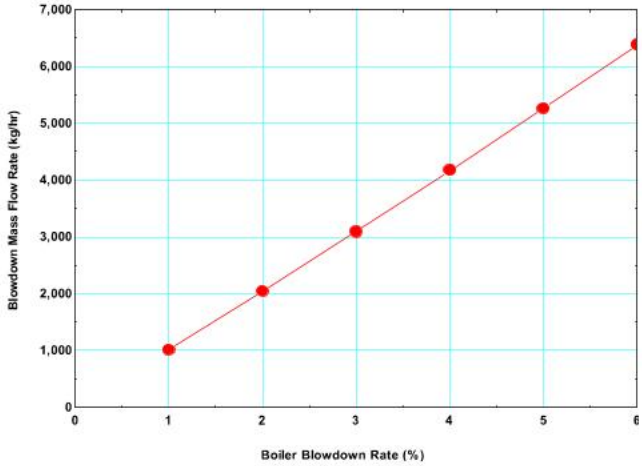
Boiler Blowdown Energy



Graph for boiler operating at 100 Tph steam flow rate

- Boiler blowdown thermal energy loss typically focuses on continuous surface blowdown
- Blowdown flow is represented as percent of feedwater flow

$$\beta = \frac{\text{Blowdown Flow}}{\text{Feedwater Flow}} \times 100$$

- Mass balance on the boiler provides blowdown flow

$$m_{\text{blowdown}} = \left(\frac{\beta}{1-\beta}\right) m_{\text{steam}}$$

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Blowdown Estimate

- It is very rare to find a flowmeter that measures blowdown
  - Blowdown stream is saturated and flashes
  - Two-phase flow is very difficult to measure
  - Flowmeters are subject to high fouling and two-phase conditions
- Chemical concentrations (such as chlorides and other chemicals) can be measured to determine blowdown rate
- These concentrations can be correlated to conductivity
- Ratio of feedwater conductivity to blowdown conductivity provides a very good estimate of boiler blowdown

Example Natural gas Boiler / Steam System

- Boiler fired with natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/m³
- Steam generation: 20 Tph (steady all year round)
- Steam conditions: 25 bars; 375°C
- Boiler feedwater: 30 bars, 110°C
- Fuel supply: 1,693 Nm³/hr (28 Nm³/min)
- Fuel cost: $1.0/Nm³
- Conductivity for blowdown = 2,000 μmhos/cm
- Conductivity for feedwater = 100 μmhos/cm
- Makeup water temperature: 20°C
- Determine the amount of blowdown and the possible energy loss?

Blowdown Energy Loss

$$\beta \approx \frac{Feedwater\ Conductivity}{Blowdown\ Conductivity} \times 100$$

$$\beta \approx \frac{100}{2{,}000} \times 100 = 5.0\%$$

$$\mathrm{m_{blowdown}} = \left(\frac{\beta}{1-\beta}\right) \mathrm{m_{steam}} = \left(\frac{0.05}{1-0.05}\right) 20{,}000 = 1{,}052\ \mathrm{kg/hr}\ =\ 0.29\ \mathrm{kg/s}$$

$$Q_{blowdown} = m_{blowdown}\left(h_{blowdown} - h_{feedwater}\right) = 0.29\ (971.8 - 463.5) = 148\ kW$$

Boiler Evaluation

$$Q_{blowdown} = m_{blowdown}\left(h_{blowdown} - h_{makeup}\right) = 0.29\ (971.8 - 83.9) = 259\ kW$$

System Evaluation

Blowdown Energy Loss

- Boiler Efficiency Evaluation

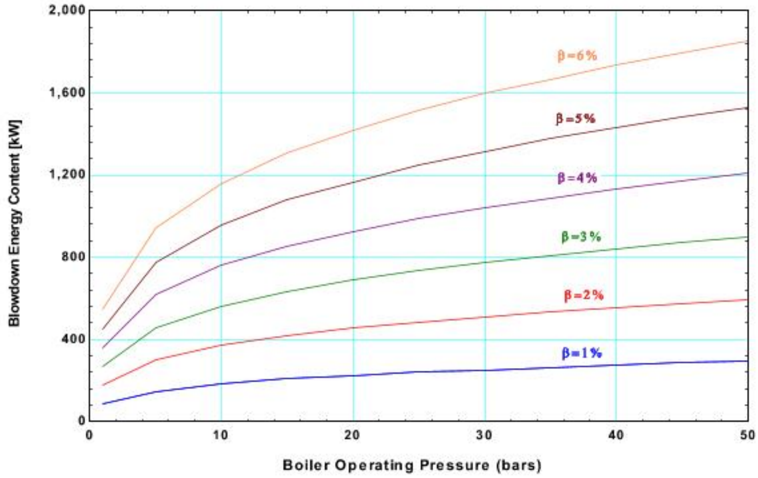
$$\lambda_{blowdown} = \frac{m_{blowdown}(h_{blowdown} - h_{feedwater})}{m_{fuel}\, HHV_{fuel}} \times 100 = \frac{0.29\,(971.8 - 46\ .5)}{1{,}693(40{,}144)} \times 3{,}600 \times 100 = 0.79\%$$

$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{0.79}{100} \times 14{,}800{,}000 \approx \$116{,}500$$

- System Efficiency Evaluation

$$\lambda_{blowdown} = \frac{m_{blowdown}(h_{blowdown} - h_{makeup})}{m_{fuel}\, HHV_{fuel}} \times 100 = \frac{0.29\,(971.8 - 83.9)}{1{,}693\,(40{,}144)} \times 3{,}600 \times 100 = 1.38\%$$

$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{1.38}{100} \times 14{,}800{,}000 \approx \$204{,}000$$



Boiler Blowdown Energy Loss

Graph for boiler operating at 100 Tph steam flow rate; Make-up Water at 20°C

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Total Steam System Blowdown Energy Loss

$$\mathrm{m_{blowdown}} = \left(\frac{\beta}{1-\beta}\right) \mathrm{m_{steam}} = \left(\frac{0.05}{1-0.05}\right) 150{,}000 = 7{,}895 \text{ kg/hr} \;=\; 2.19 \text{ kg/s}$$

- Will require total fuel energy supplied to all the boilers
  - Can be calculated by doing analysis on each boiler or using average boiler efficiency
  - Example system - 486.0 GJ/hr
- Will require total fuel cost for all the boilers
  - Can be calculated by doing analysis on each boiler or using average fuel cost
  - Example system - 6,605 $/hr

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Total Steam System Blowdown Energy Loss

- Boiler Efficiency Evaluation

$$\lambda_{blowdown} = \frac{m_{blowdown}\left(h_{blowdown} - h_{feedwater}\right)}{m_{fuel}\,HHV_{fuel}} \times 100 = \frac{2.19\,(971.8 - 463.5)}{486 \times 1000 \times 1000} \times 3{,}600 \times 100 = 0.80\%$$

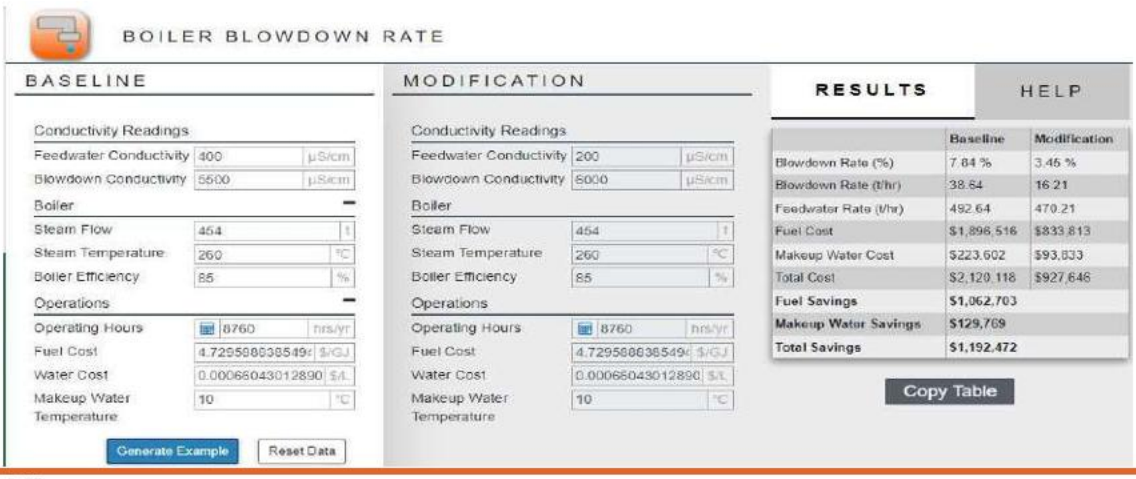
$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{0.80}{100} \times 6{,}605 \times 8{,}760 \approx \$463{,}000$$

- System Efficiency Evaluation

$$\lambda_{blowdown} = \frac{m_{blowdown}\left(h_{blowdown} - h_{makeup}\right)}{m_{fuel}\,HHV_{fuel}} \times 100 = \frac{2.19\,(971.8 - 83.9)}{486 \times 1{,}000 \times 1{,}000} \times 3{,}600 \times 100 = 1.40\%$$

$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{1.40}{100} \times 6{,}605 \times 8{,}760 \approx \$833{,}000$$

MEASUR Calculator – Boiler Blowdown



Stack Losses

- Stack losses are the largest of the boiler losses
- Stack losses are made up of two parts and defined as Backpressure
  - Temperature losses
  - Combustion losses
- Combustion analysis is the method generally used to determine stack losses

Stack Loss Evaluation & Opportunities

- Need a minimum number of measurements
- Can be via in-situ or portable instruments
- These measurements include:
  - Stack exhaust gas temperature
  - Flue gas oxygen content
  - Ambient temperature
  - Fuel composition
  - Flue gas combustibles concentration
- Stack loss tables
- Combustion models (software)

Stack Loss Table for			Typical Natural Gas											
Flue Gas Oxygen Content Wet Basis [%]	Flue Gas Oxygen Content Dry Basis [%]	Comb Conc [ppm]	Stack Loss [% of fuel Higher Heating Value input] Net Stack Temperature [Δ°C] {Difference between flue gas exhaust temperature and ambient temperature}											
			100	128	156	183	211	239	267	294	322	350	378	406
1.0	1.2	0	13.6	14.7	15.8	16.9	18.0	19.1	20.2	21.3	22.4	23.6	24.7	25.9
2.0	2.4	0	13.8	14.9	16.1	17.2	18.4	19.5	20.7	21.9	23.1	24.2	25.4	26.6
3.0	3.6	0	14.0	15.2	16.4	17.6	18.8	20.0	21.3	22.5	23.7	25.0	26.3	27.5
4.0	4.7	0	14.2	15.5	16.7	18.0	19.3	20.6	21.9	23.2	24.5	25.8	27.2	28.5
5.0	5.8	0	14.5	15.8	17.2	18.5	19.9	21.2	22.6	24.0	25.4	26.8	28.2	29.6
6.0	6.9	0	14.8	16.2	17.6	19.1	20.5	22.0	23.4	24.9	26.4	27.8	29.3	30.8
7.0	8.0	0	15.1	16.6	18.1	19.7	21.2	22.8	24.3	25.9	27.5	29.1	30.7	32.3
8.0	9.1	0	15.5	17.1	18.8	20.4	22.1	23.7	25.4	27.1	28.8	30.5	32.2	33.9
9.0	10.1	0	16.0	17.7	19.5	21.2	23.0	24.8	26.6	28.5	30.3	32.1	34.0	35.8
10.0	11.1	0	16.5	18.4	20.3	22.2	24.2	26.1	28.1	30.1	32.1	34.1	36.1	38.1
Actual Exhaust T [°C]			121	149	177	204	232	260	288	316	343	371	399	427
Ambient T [°C]			21	21	21	21	21	21	21	21	21	21	21	21

Stack Loss - Natural Gas

- Stack loss table is developed for negligible combustibles and no condensation

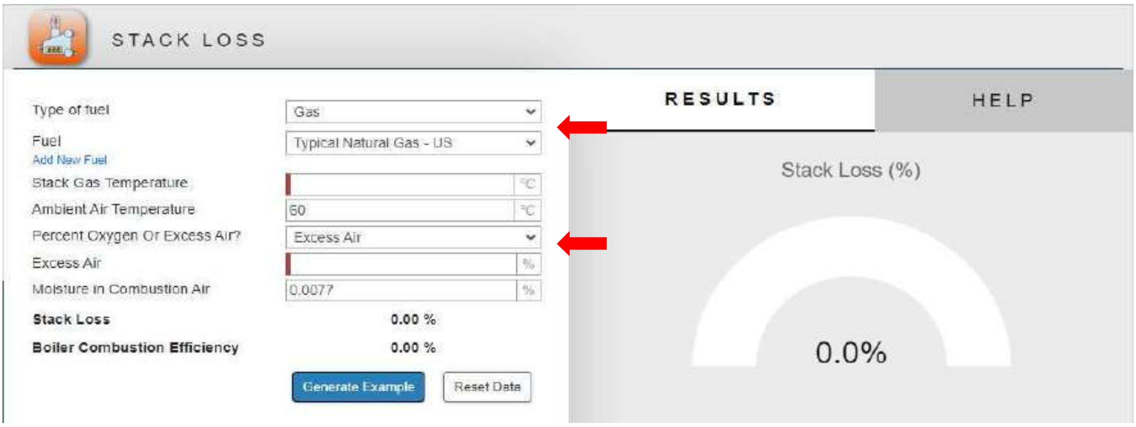
Reference: Combustion model developed by Greg Harrell, Ph.D., P.E.

Stack Loss using US DOE MEASUR

- Use US DOE MEASUR to determine stack loss and combustion efficiency

$$\eta_{combustion} = 100 - \lambda_{stack}$$

MEASUR – Stack Loss Calculator



NOT limited to Steam boilers; Can be used for direct-fired process heaters, furnaces, etc

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Example Natural gas Boiler

- Boiler fired with natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/m^3
- Steam generation: 20 Tph (steady all year round)
- Steam pressure: 25 bars; 375°C
- Boiler feedwater: 30 bars, 110°C
- Fuel supply: 1,693 Nm^3/hr (28 Nm^3/min)
- Fuel cost: $1.0/Nm3
- Stack temperature: 200°C
- Flue gas oxygen: 5%
- Negligible combustibles were found in stack gas analysis
- Ambient air temperature: 20°C
- **Determine the stack loss and identify possible energy saving opportunities?**

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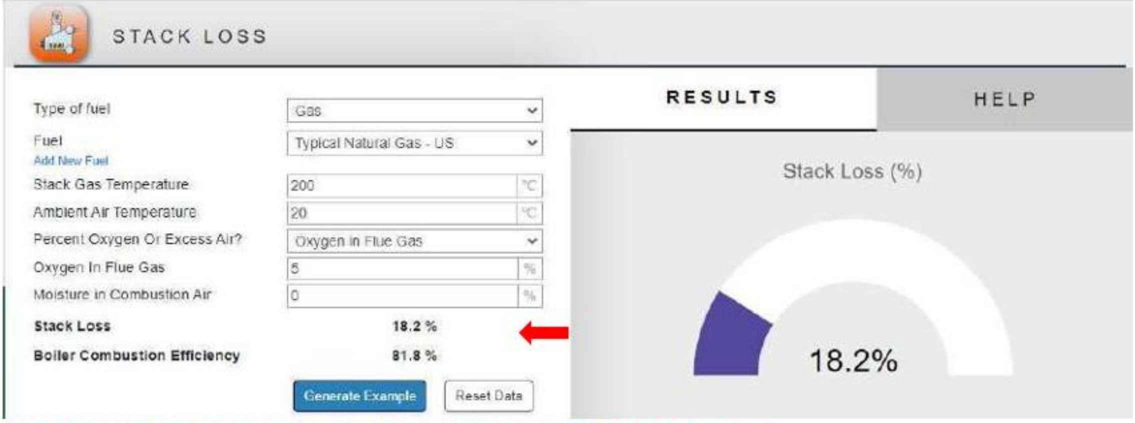
Stack Loss - Natural Gas



DO NOT use Moisture in Combustion Air – there is an error in that formulae

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Example Natural Gas Boiler Efficiency

$$\eta_{boiler} = 100 - Losses$$

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

$$\eta_{boiler} = 100 - 0.5 - 0.79 - 18.2 - 0$$

$$\eta_{boiler} = 80.5\%$$

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Example MEASUR Boiler Efficiency

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

FIXED (Magnitude)
Does NOT change for IMPACT analysis

MEASUR calculates this internally

$$\eta_{MEASUR\_boiler} = 100 - \lambda_{stack} - \lambda_{other}$$

$$\eta_{MEASUR\_boiler} = 100 - 18.2 - 0$$

$$\eta_{MEASUR\_boiler} = 81.8\%$$

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Example System Coal Sample

Component	Mole Fraction [kmoli/kmolfuel]	Mass Fraction [kgmi/kgmfuel]	Molecular Weight [kgm/kmol]
C	0.4942	0.4400	12.000
H_2	0.3677	0.0550	2.016
CH_4	0.0000	0.0000	16.043
N_2	0.0144	0.0300	28.013
CO	0.0000	0.0000	28.011
C_2H_4 (Ethylene)	0.0000	0.0000	28.054
C_2H_6 (Ethane)	0.0000	0.0000	30.020
C_3H_8 (Propane)	0.0000	0.0000	44.097
O_2	0.0295	0.0700	31.999
S	0.0021	0.0050	32.060
H_2O (intrinsic)	0.0374	0.0500	18.015
H_2O (extrinsic)	0.0000	0.0000	18.015
CO_2	0.0000	0.0000	44.010
$C_6H_{10}O_5$ (Cellulose)	0.0000	0.0000	162.140
Ash (Total)	0.0546	0.3500	
Ash Components			
Al_2O_3	0.0097	0.0735	101.961
SiO_2	0.0345	0.1540	60.085
Fe_2O_3	0.0103	0.1225	159.692
Total	1.0000	1.0000	
Fuel Molecular Weight	13.4790	kgfuel/kmolfuel	
HHV	9,582 Btu/lbm	22.28 MJ/kgh	5,322 kcal/kg
LHV	9,013 Btu/lbm	20.96 MJ/kgh	5,006 kcal/kg

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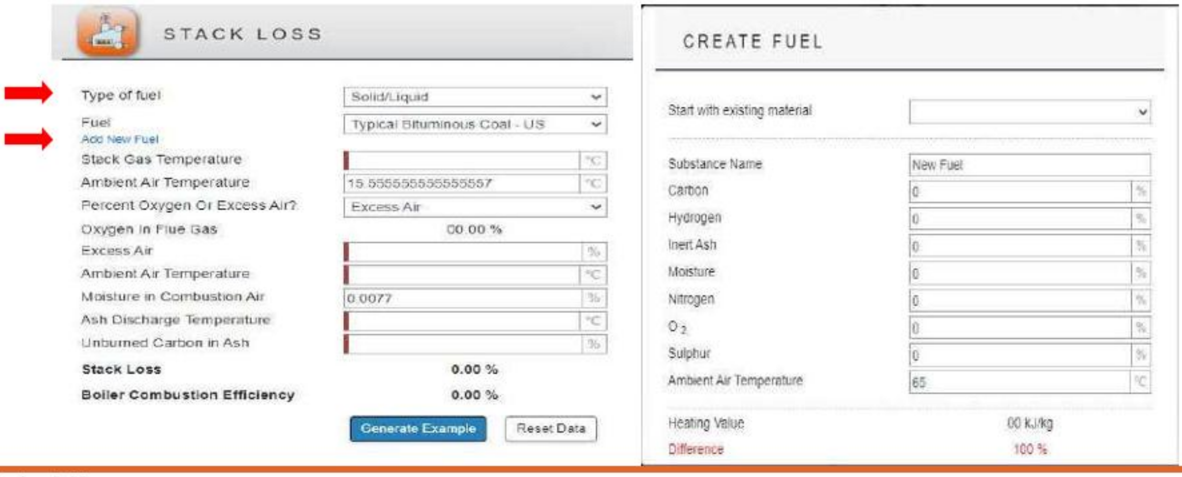
Stack Loss – Example System Coal

- Stack loss table is developed for negligible combustibles and no condensation

Stack Loss Table for			Example System Coal											
Flue Gas Oxygen Content Wet Basis	Flue Gas Oxygen Content Dry Basis	Comb Conc	Stack Loss [% of fuel Higher Heating Value input] Net Stack Temperature [Δ°C] {Difference between flue gas exhaust temperature and ambient temperature}											
[%]	[%]	[ppm]	100	128	156	183	211	239	267	294	322	350	378	406
1.0	1.1	0	9.7	10.8	11.8	12.9	14.0	15.1	16.2	17.4	18.5	19.6	20.8	21.9
2.0	2.2	0	9.9	11.0	12.1	13.3	14.4	15.6	16.7	17.9	19.1	20.3	21.4	22.6
3.0	3.4	0	10.1	11.2	12.4	13.6	14.8	16.0	17.3	18.5	19.7	21.0	22.2	23.5
4.0	4.4	0	10.3	11.5	12.8	14.0	15.3	16.6	17.9	19.2	20.5	21.8	23.1	24.4
5.0	5.5	0	10.5	11.8	13.2	14.5	15.8	17.2	18.5	19.9	21.3	22.7	24.0	25.4
6.0	6.6	0	10.8	12.2	13.6	15.0	16.4	17.9	19.3	20.7	22.2	23.7	25.1	26.6
7.0	7.6	0	11.1	12.6	14.1	15.6	17.1	18.6	20.2	21.7	23.3	24.8	26.4	28.0
8.0	8.6	0	11.5	13.1	14.7	16.3	17.9	19.5	21.2	22.8	24.5	26.2	27.8	29.5
9.0	9.7	0	11.9	13.6	15.3	17.1	18.8	20.6	22.4	24.1	25.9	27.7	29.5	31.3
10.0	10.7	0	12.4	14.3	16.1	18.0	19.9	21.8	23.7	25.7	27.6	29.6	31.5	33.5
Actual Exhaust T [°C]			121	149	177	204	232	260	288	316	343	371	399	427
Ambient T [°C]			21	21	21	21	21	21	21	21	21	21	21	21

Reference: Combustion model developed by Greg Harrell, Ph.D., P.E.

MEASUR Stack Loss – User Defined Fuel



Unburned Fuel Loss

- Fuels containing ash commonly present an energy loss in the form of unburned fuel in the ash
  - The unburned fuel component is typically carbon
    - The other fuel components are generally more reactive than carbon
      - Also carbon is usually the dominant fuel component

Loss On Ignition (LOI) Analysis

1. Measure the mass of the raw collected sample (ash and carbon)
2. Expose the collected sample to a combustion source for an extended period to ensure all combustible material has reacted
3. Measure the mass of the remaining sample, which is ash alone.

$$LOI = \frac{m_{Carbon}}{m_{Carbon} + m_{Ash\ alone}} = \frac{m_C}{m_C + m_A} = \frac{m_C}{m_{Full\ Sample}}$$

$$m_C = \frac{LOI\ (m_A)}{(1 - LOI)}$$

Loss On Ignition (LOI) Analysis

$$m_C = \frac{LOI\ (m_A)}{(1 - LOI)}$$

$$\frac{m_C}{m_{Fuel}} = \varphi_{uf} = \frac{LOI\left(\frac{m_A}{m_{Fuel}}\right)}{(1 - LOI)}$$

$$\lambda_{uf} = \phi_{uf}\frac{HHV_c}{HHV_{fuel}}$$

$$\lambda_{uf} = \phi_{uf}\frac{32{,}806\ \frac{kJ}{kg}}{HHV_{fuel}}$$

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Example System

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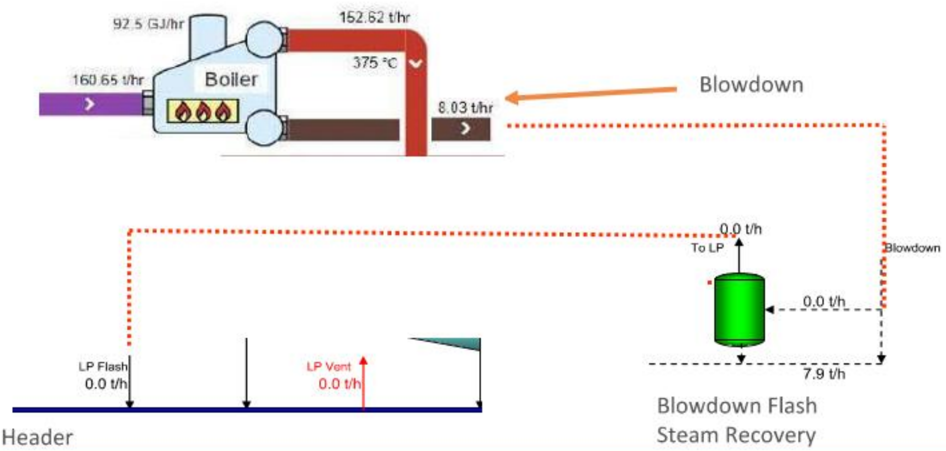
Blowdown & Flash Steam Recovery

- Blowdown Rate is given as a percentage of feedwater flow
  - Typically refers to the continuous blowdown flow
  - Calculations were done in the "Boiler Efficiency" section
- Flash steam can be recovered at low pressure (or deaerator) level
  - Use pull-down menu to include it in the system

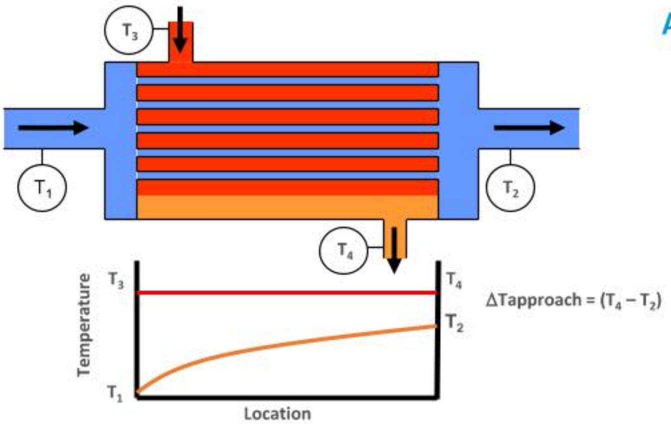
Blowdown & Flash Steam Recovery



Heat Recovery Component

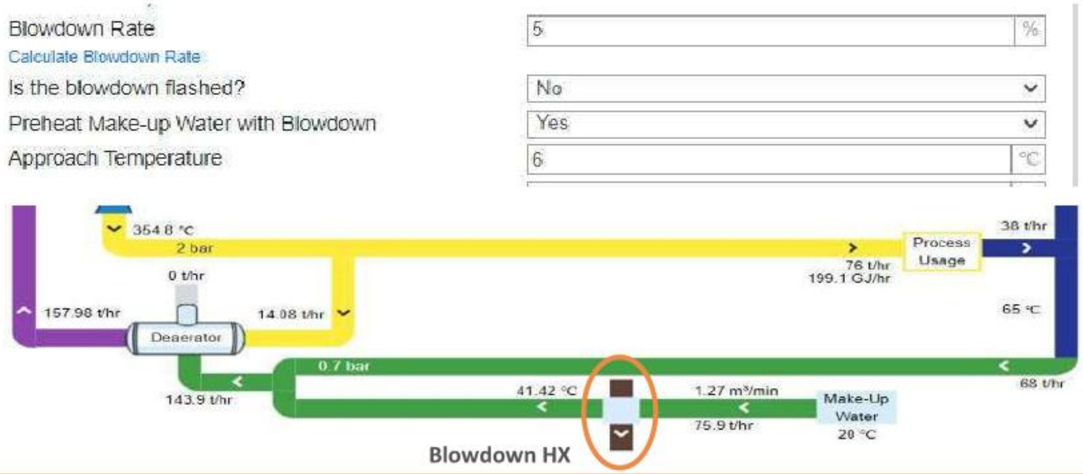
- There could be multiple heat exchanger-based recovery components that can be modeled in MEASUR
- One example is the Boiler blowdown heat exchanger
- The heat exchanger increases the make-up water temperature to the deaerator and thereby, reduces amount of deaerator steam requirement

Approach Temperature



- Heat exchanger approach temperature is defined as the **minimum allowable** temperature difference in the heat exchanger
  - This temperature difference will not be satisfied if the energy content of the recovered stream is insufficient
  - Typical values of approach temperature are 3°C to 10°C

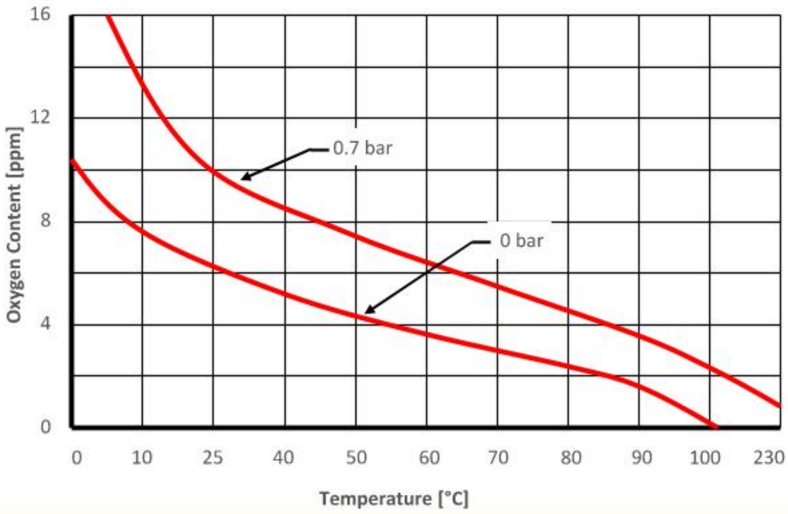
Boiler Blowdown Heat Recovery Exchanger



Example System

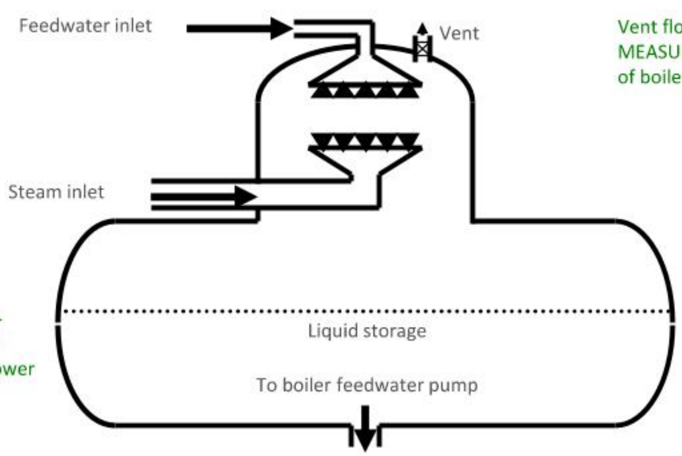
Deaeration

- Oxygen, carbon dioxide and other gases are soluble in water
  - These chemicals are detrimental to the steam system
    - Oxygen results in corrosion generally in the form of pitting
    - Carbon dioxide results in corrosion generally from acidic condensate
- Open condensate receivers are a location where gases can become dissolved in condensate
- Makeup water usually contains significant amounts of dissolved gases
- The solubility of gases in water decreases as temperature increases
  - Deaeration is used to reduce the effects of dissolved gases



Solubility of Oxygen in Water

Deaerator



Vent flow is specified in MEASUR as a percentage of boiler feedwater flow

Deaerator receives low-pressure steam but can operate at a pressure lower than this

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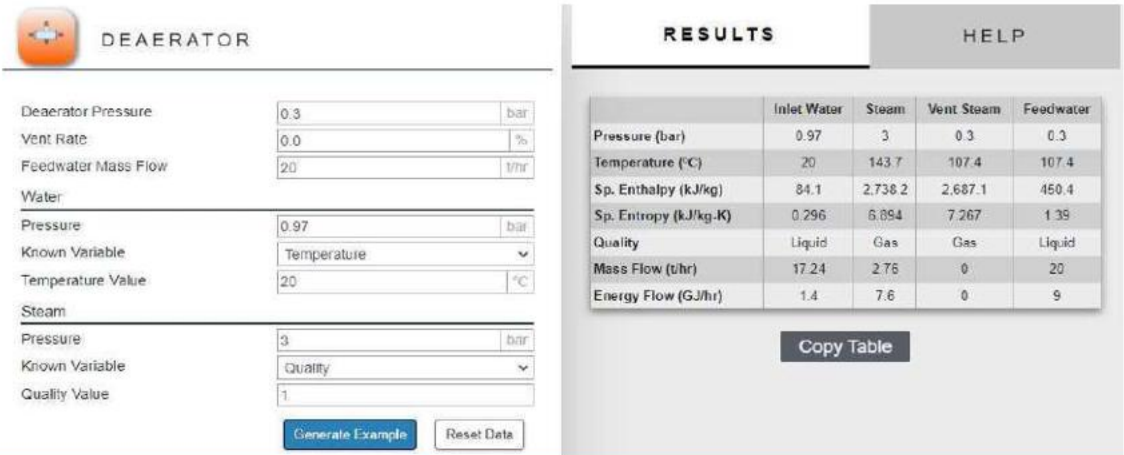
MEASUR Calculator - Deaerator



	Inlet Water	Steam	Vent Steam	Feedwater
Pressure (bar)	0.97	3	0.3	0.3
Temperature (°C)	20	143.7	107.4	107.4
Sp. Enthalpy (kJ/kg)	84.1	2,738.2	2,687.1	450.4
Sp. Entropy (kJ/kg-K)	0.296	6.894	7.267	1.39
Quality	Liquid	Gas	Gas	Liquid
Mass Flow (t/hr)	17.24	2.76	0	20
Energy Flow (GJ/hr)	1.4	7.6	0	9

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Process Steam Demand Evaluation

- MEASUR is a “pull type” model
  - Process steam flows “pull” steam through the boiler
  - Typically modeling activities strive to match general boiler load
- Process steam flows are established by:
  - Direct continuous flow measurement
  - Direct intermittent flow measurement
  - Mass balance
  - Energy balance
  - System or Process design information
  - Empirical standards or data

Flow Measurements

- Steam flow measurement is typically completed by conventional flow meters
  - Orifice plates
  - Vortex generators
- Condensate flow measurement is often completed by intermittent field observations
  - Timed volume capture
    - Condensate receiver fill and discharge
    - Known volume fill

Mass & Energy Balances

- Conservation of mass principle can often be applied very effectively

  $\Sigma \dot{m}_i = \Sigma \dot{m}_e$

- The first law of thermodynamics (energy balance) for heat exchange is typically applied to:
  - Steam alone
  - Heated material alone

$$\dot{Q}_x = \dot{m}_x (C_p)_x (T_e - T_i)_x \Big\}$$ For constant specific heats and when enthalpy is a function of temperature only

$$\dot{Q}_x = \dot{m}_x (h_e - h_i)_x \Big\}$$ When material enthalpies are known

$$\dot{Q}_{steam} = -\dot{Q}_x \Big\}$$ Typical heat exchanger applications

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Example Steam System

- Pressure levels for steam distribution (end use)
  - High pressure – 25 bars (g)
  - Medium pressure – 10 bars (g)
  - Low pressure – 2 bars (g)
- Process Demands
  - High pressure – 20 Tph
  - Medium pressure – 40 Tph
  - Low pressure – 76 Tph
- Assume “NO” Desuperheating
- Assume “NO” heat loss from system headers

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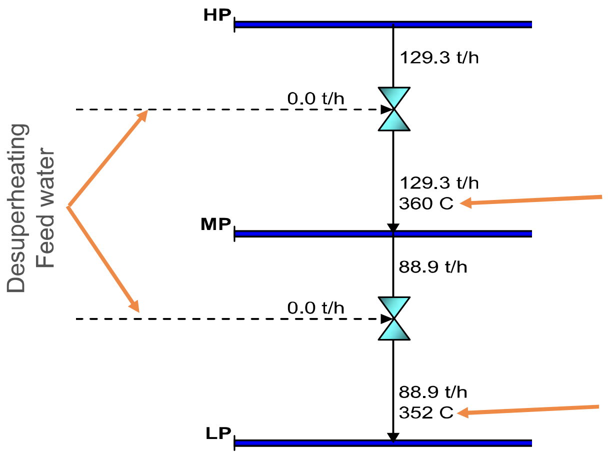
Letdowns / PRVs

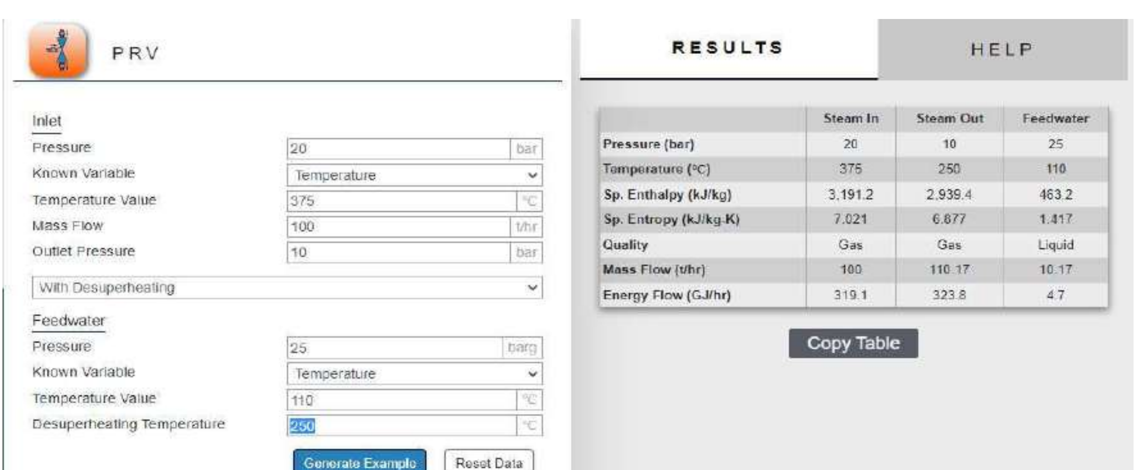
- Pressure Reducing Valves (PRVs) are most prevalent method of reducing pressure in a steam system
- A steam system will have one or more PRVs between two headers
- Not all PRVs maybe controlling header pressures



Letdowns / PRVs

- Steam temperature at the outlet of the PRVs is controlled by feedwater (Desuperheaters)
- Mainly done for
  - Protecting equipment
  - Design conditions
  - Reducing pressure drop

MEASUR Calculator – Pressure Reducing Valve



	Steam In	Steam Out	Feedwater
Pressure (bar)	20	10	25
Temperature (°C)	375	250	110
Sp. Enthalpy (kJ/kg)	3,191.2	2,939.4	463.2
Sp. Entropy (kJ/kg-K)	7.021	6.877	1.417
Quality	Gas	Gas	Liquid
Mass Flow (t/hr)	100	110.17	10.17
Energy Flow (GJ/hr)	319.1	323.8	4.7

MEASUR Calculator – Heat Loss

HEAT LOSS

Pressure	25 bar
Known Variable	Temperature
Temperature Value	375 °C
Mass Flow	20 t/hr
% Heat Loss	1 %

Generate Example | Reset Data

RESULTS | HELP

Percent Loss	1 %	
Heat Loss	0.6 GJ/hr	
	Inlet steam	Outlet Steam
Pressure (bar)	25	25
Temperature (°C)	375	361
Phase	Gas	Gas
Mass Flow (t)	20	20
Specific Enthalpy (kJ/kg)	3,181.9	3,150.1
Specific Entropy (kJ/kg-K)	6.911	6.862
Energy Flow (GJ/hr)	63.6	63

Copy Table

Example Steam System

- Condensate Return
  - Temperature – 65°C
  - Temperature in the condensate return tank or in the condensate return header going to the deaerator
- Condensate Recovery
  - On all headers is 50%
- No condensate is flashed
- Assume “NO” steam turbines in the system

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Process Condensate

- The condensate receiver operates at atmospheric pressure
- The condensate return temperature provides an indication of the energy loss associated with the condensate return system
- Condensate recovery percentage describes the amount of *process steam* recovered in the condensate system
- Flash steam recovery systems allow recovered condensate to flash steam into lower-pressure steam systems
- Makeup water temperature impacts condensate related projects

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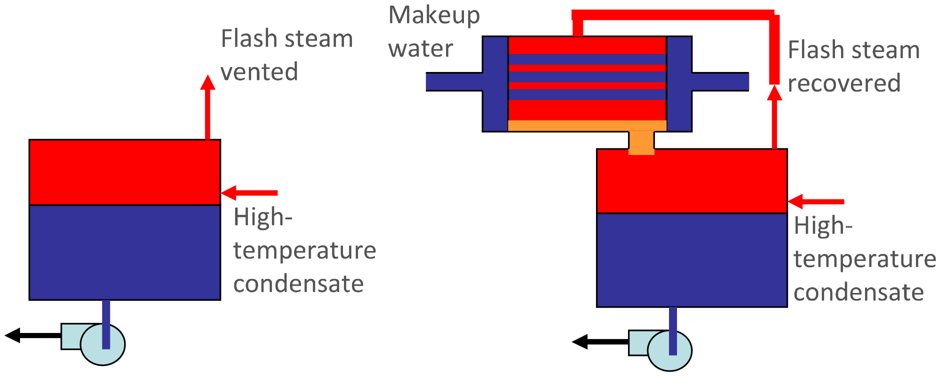
Condensate Tank Vent Exchanger

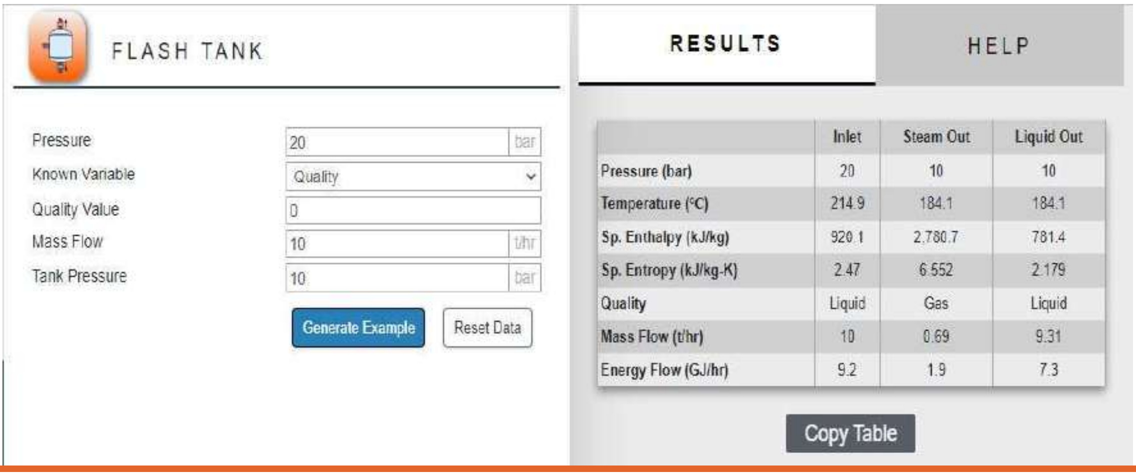
- The condensate receiver operates at atmospheric pressure
  - Condensate entering the receiver with a temperature greater than atmospheric pressure saturation temperature (100°C) will flash
    - This flash steam can be recovered by make-up water energy recovery

Condensate Tank Vent Exchanger (cont.)

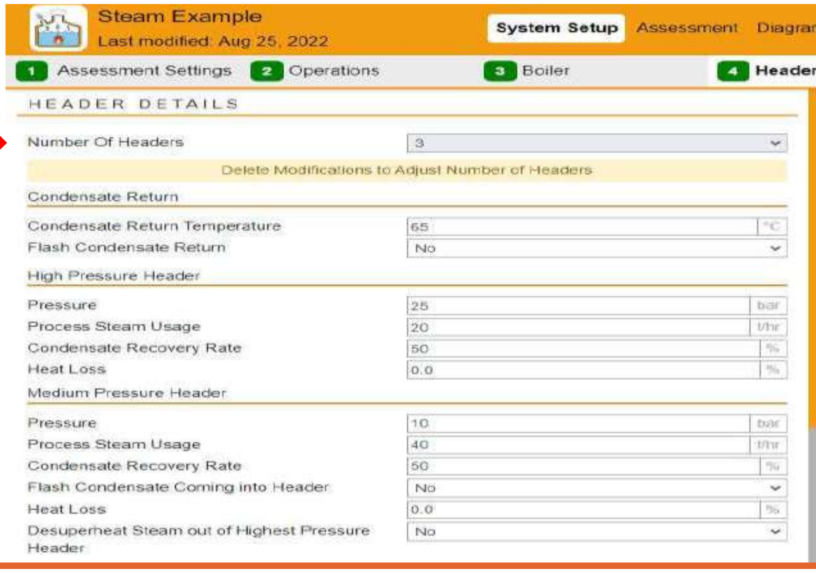


Condensate Receiver Vent Loss **Condensate Receiver Energy Recovery**

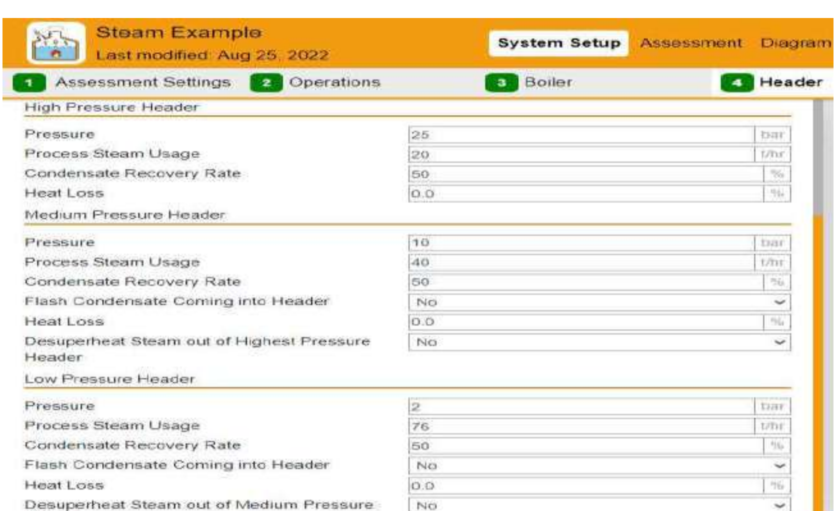
MEASUR Calculator – Flash Tank



	Inlet	Steam Out	Liquid Out
Pressure (bar)	20	10	10
Temperature (°C)	214.9	184.1	184.1
Sp. Enthalpy (kJ/kg)	920.1	2,780.7	781.4
Sp. Entropy (kJ/kg-K)	2.47	6.552	2.179
Quality	Liquid	Gas	Liquid
Mass Flow (t/hr)	10	0.69	9.31
Energy Flow (GJ/hr)	9.2	1.9	7.3



Example System



Example System

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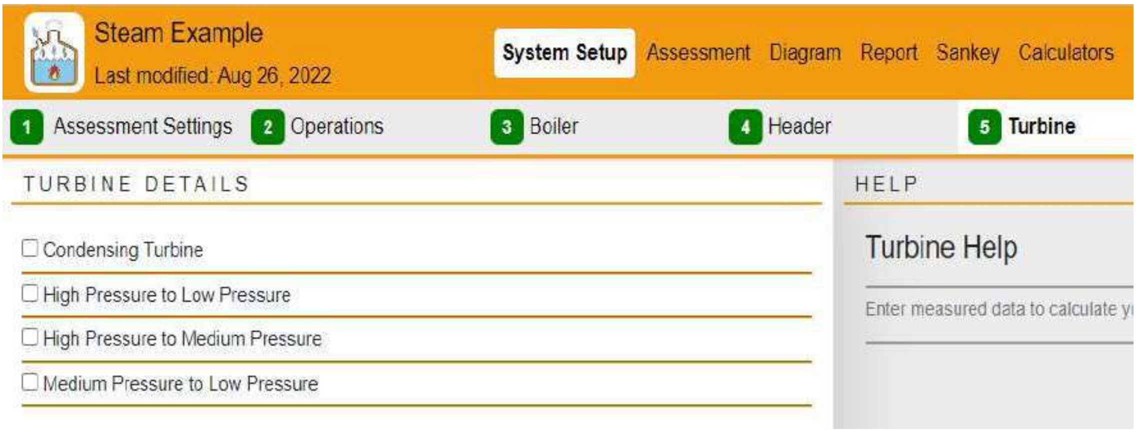
Example System



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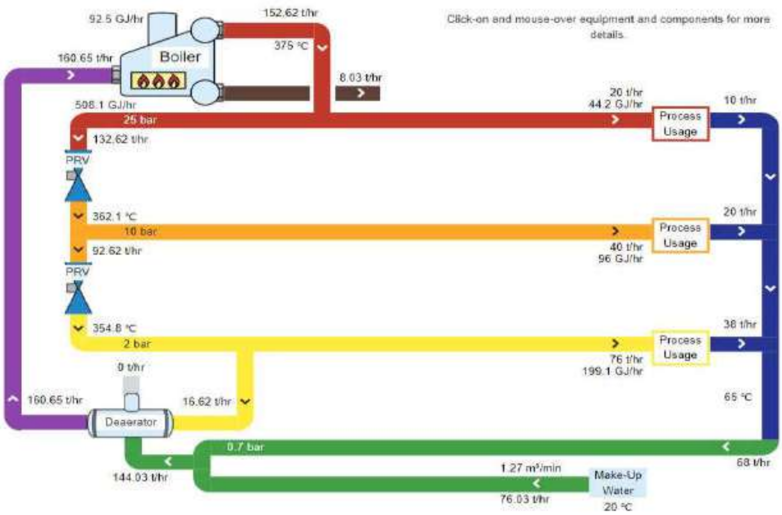

Example System

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Low-pressure Header Vent

- The low-pressure header can operate in an "unbalanced" state
  - This can develop in steam systems by:
    - Operating more backpressure turbines than necessary
    - Poor control strategies
  - The low-pressure vent should always be a point of investigation
    - From the physical site operations standpoint
    - From the MEASUR model standpoint

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STEAM SYSTEM SUMMARY

Steam Generated	
152.6 t/hr	
Total Operating Cost	
$116,097,582	

CO_2 Emissions (tonne CO_2/yr)	
Emissions From Fuel	223,845.22
Emissions From Selling Electricity	0
Emissions From Change in Electricity Imports	0
Total Emissions	223,845.22

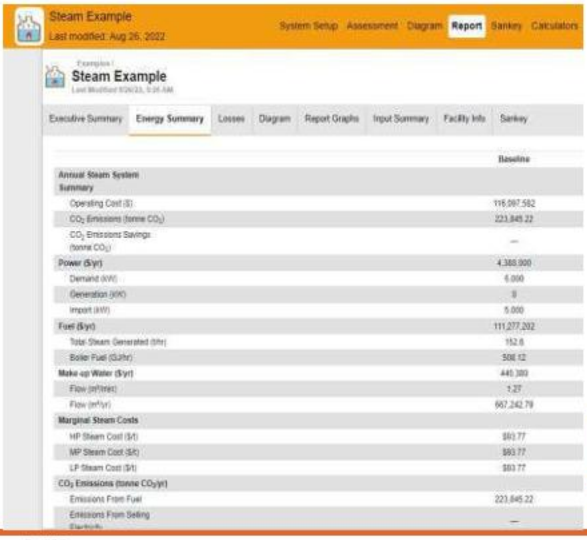
Fuel	
Boiler Fuel Use	4,451,088.07 GJ/yr
Boiler Fuel Cost ($)	$111,277,202

Electricity	
Electricity Generated	0 kW
Electricity Imported	5,000 kW
Electricity Cost ($)	$4,380,000

Make-Up Water	
Make-Up Water Required	667,242.79 m³
Make-up Water Cost ($)	$440,380

Example System

- Do we agree with all these numbers?
- If yes, which ones do we agree?
- If no, which ones do we NOT agree?



Steam Example
Last modified: Aug 26, 2022
System Setup | Assessment | Diagram | Report | Sankey | Calculators

Examples /
Steam Example

Executive Summary | Energy Summary | Losses | Diagram | Report Graphs | Input Summary | Facility Info | Sankey

	Baseline
Annual Steam System Summary	
Operating Cost ($)	116,097,582
CO_2 Emissions (tonne CO_2)	223,845.22
CO_2 Emissions Savings (tonne CO_2)	—
Power ($/yr)	4,380,000
Demand (kW)	6,000
Generation (kW)	0
Import (kW)	5,000
Fuel ($/yr)	111,277,202
Total Steam Generated (t/hr)	152.6
Boiler Fuel (GJ/hr)	508.12
Make-up Water ($/yr)	440,380
Flow (m^3/min)	1.27
Flow (m^3/yr)	667,242.79
Marginal Steam Costs	
HP Steam Cost ($/t)	$93.77
MP Steam Cost ($/t)	$93.77
LP Steam Cost ($/t)	$93.77
CO_2 Emissions (tonne CO_2/yr)	
Emissions From Fuel	223,845.22
Emissions From Selling Electricity	—

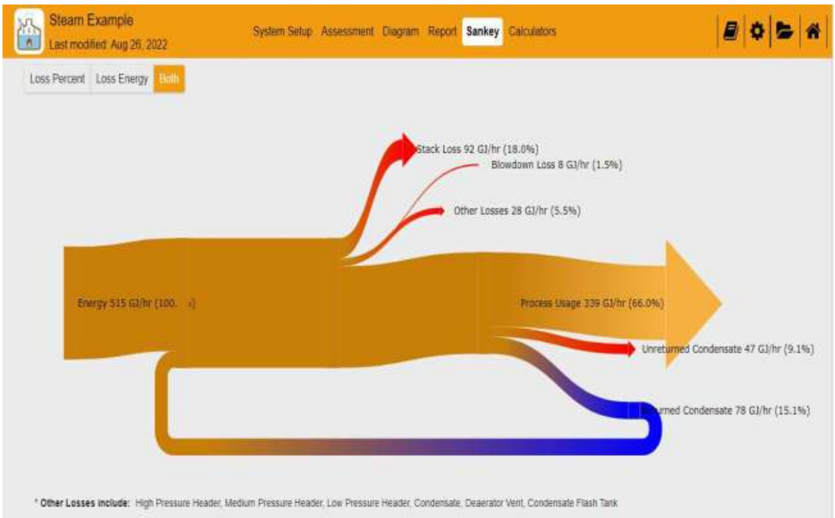
Example System

- Remember: Impact Analysis

Do we agree with all these numbers?
If yes, which ones do we agree?
If no, which ones do we NOT agree?

Marginal Steam Costs

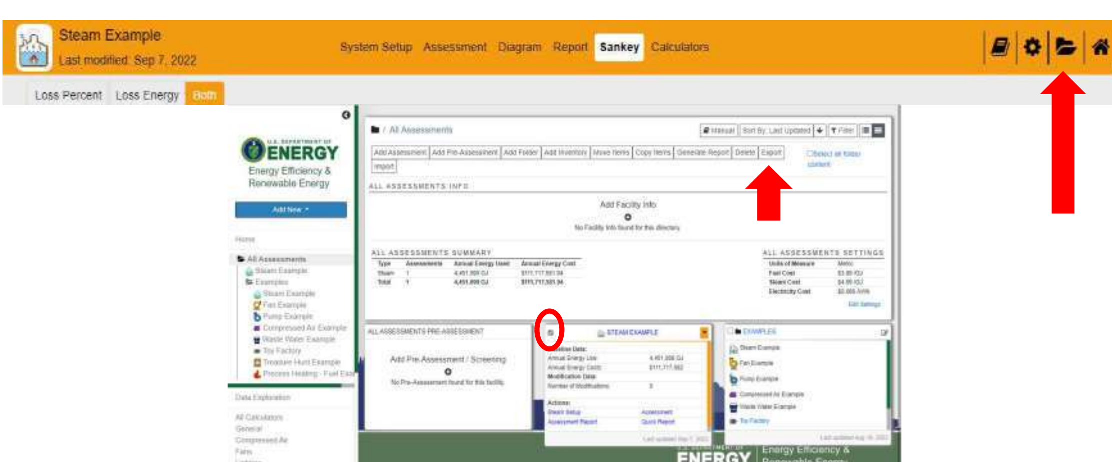
- Marginal costs are determined based on supplying an additional 1 Tph of additional steam from a header
- Marginal steam costs are typically used when analyzing
  - Steam leaks
  - Process changes
  - Elimination or institution of nominal steam use
- Marginal steam costs are impacted by condensate return – Amount; Temperature



Example System – Sankey Plot

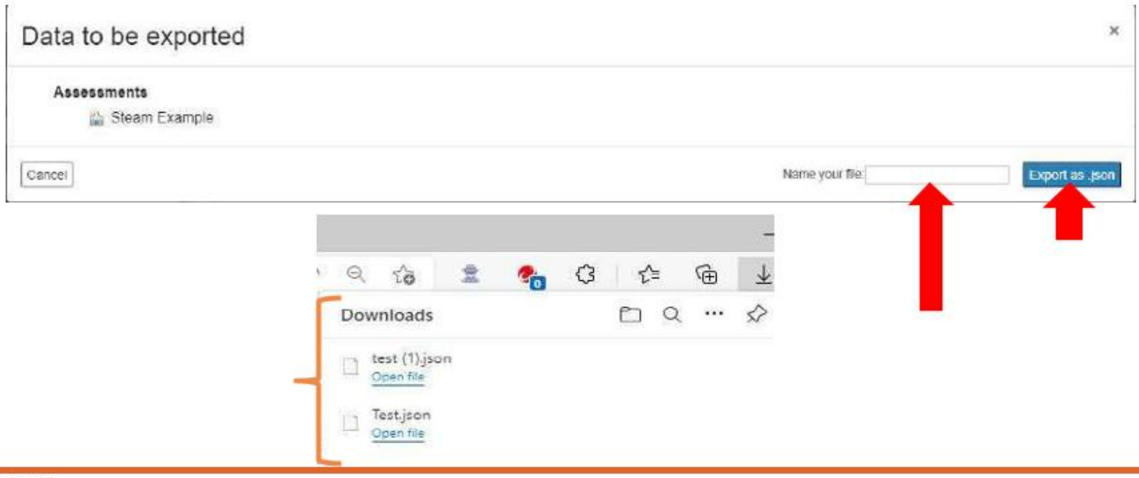
Section_3_135

Saving the Assessment File – Very Important!



Section_3_136

Saving the Assessment File – Very Important!



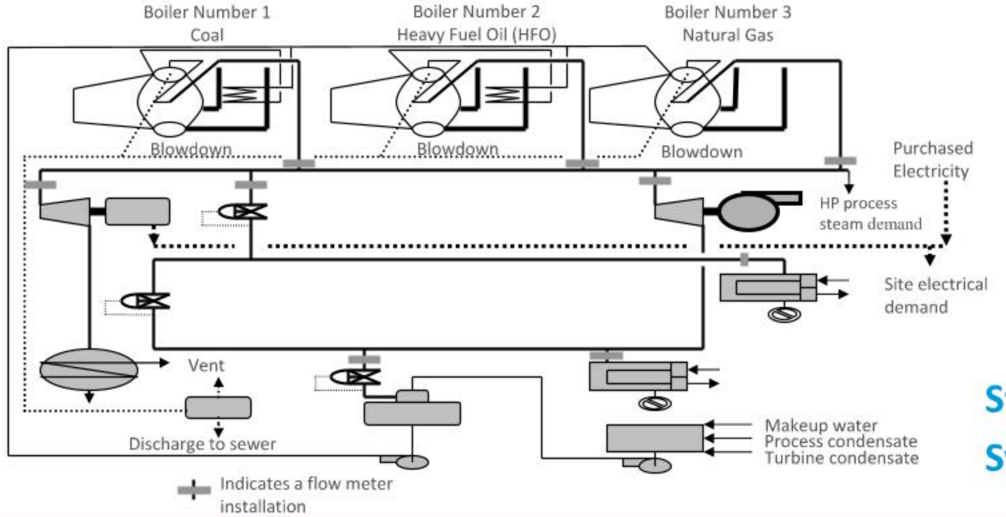
MEASUR 1-Header Model Student Exercise

- Using the example system with the Natural gas boiler as the impact boiler, build a model to accurately reflect steam impact (marginal) costs and economic benefits of saving 1 Tph of steam
- Steam generated ~20 Tph from the Natural gas boiler
- Steam conditions: 25 bars, 375°C
- Make up water: 20°C
- Condensate temperature: 65°C
- Condensate return: 50%

Section 4: Combined Heat & Power (Cogeneration)

- Fundamentals of Turbines
- Backpressure Turbines
- Modeling Backpressure Turbines in MEASUR
- Hands-On Student Exercise
- Condensing Turbines
- Modeling Condensing Turbines in MEASUR

Steam System



What is a Turbine?

- Energy Conversion Device

Potential / Kinetic / Pressure / Thermal Energy

Rotational Shaft Energy

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Users of Steam Turbines in Industry

- Heavy Steam Turbine Users
  - Petrochemicals
  - Petroleum Refining
  - Forest Products (Pulp & Paper)
  - Rubber
  - Pharmaceuticals
  - Manufacturing Assembly
- Medium & Small Steam Turbine Users
  - Food & Beverage
  - Plastics
  - Electronics
  - Metal Fabrication

Steam turbine drives commonly used in industry

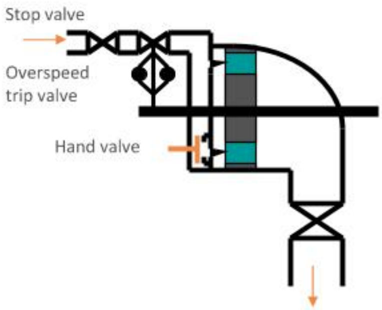
- Direct power generation
- Boiler feed water pumps
- Cooling tower water pumps
- Chilled water pumps
- Boiler forced draft fans
- Exhaust fans
- Air compressors
- Refrigeration machines
- Chiller systems
- Other utility services

Steam Turbines

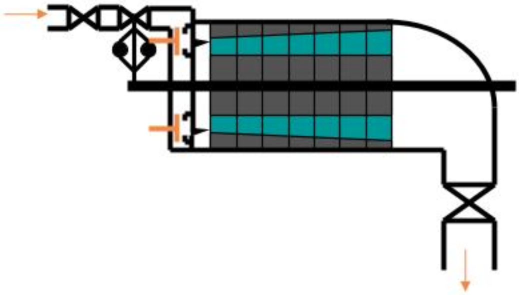
- Many different kinds
  - Backpressure
  - Condensing
  - Extraction
  - Combination
- Different size and efficiency ranges
- Backpressure turbines are used in lieu of letdown stations and in parallel with letdown stations
- Condensing turbines provide maximum shaft power per unit of steam flow

Backpressure Steam Turbines

- Backpressure steam turbines discharge steam at a pressure greater than (or equal to) atmospheric pressure



Single Stage Backpressure Turbine



Multistage Backpressure Turbine

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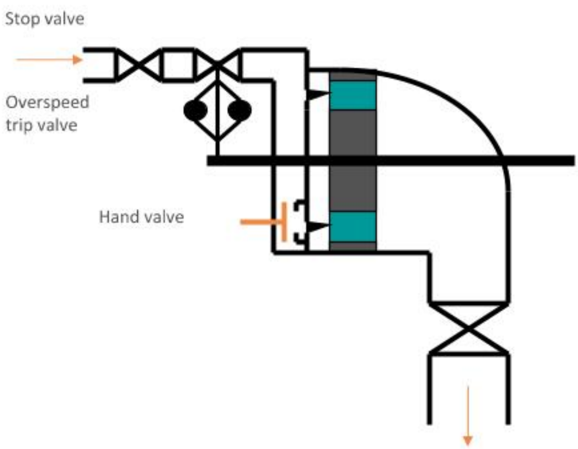
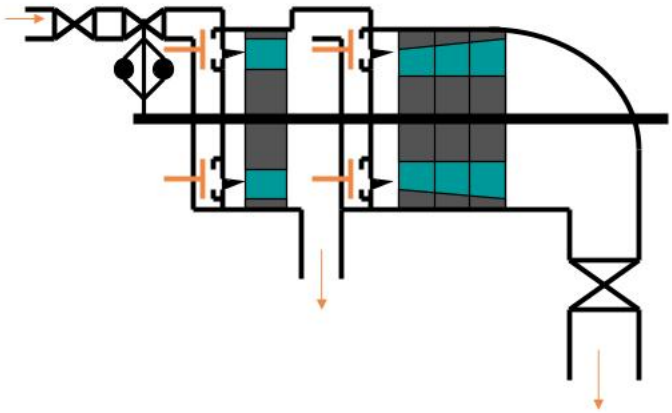
Backpressure Steam Turbines



Single Stage Backpressure Turbine

- Very common
- Simplest form
- Works against a backpressure
- Exhausts to a process load or steam header
- An excellent candidate for industrial applications

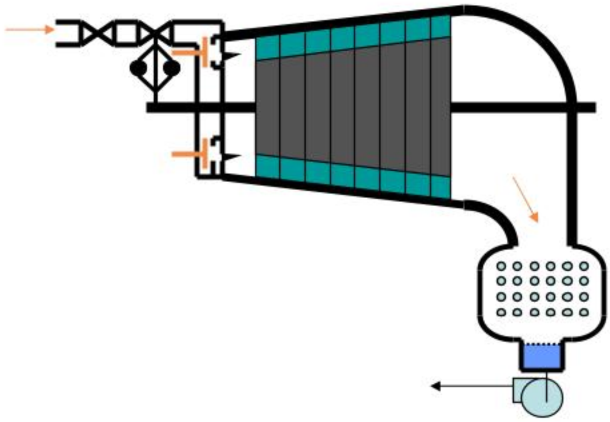
Extraction Steam Turbines



Extraction Turbine

- Very common in plants that have multiple steam pressure headers
- Works against a backpressure
- Exhausts to a process load, steam header or a condenser
- An excellent candidate for balancing headers & eliminating steam venting

Condensing Steam Turbines



Condensing Turbine

- The industry workhorse for power generation
- Will always have an associated steam condenser
- Exhausts to vacuum
- Highest operating pressure ratios
- Multistage and may even have two or three sections
- Very large sizes
- Lowest steam rates

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Typical Industrial Steam Turbines Operations

- Operating pressures
  - Minimum – 10 bars (for backpressure)
  - Maximum – 100 bars
  - Vacuum conditions can exist at the exhaust!
- Operating steam temperatures
  - Saturated or a few degrees of superheat
  - Maximum – 200°C superheat
- Summary – Steam turbine technology is very diverse and operates over a broad range of pressures and temperatures

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Turbine First Law Efficiency

- An energy balance conducted on a steam turbine will reveal an exceptionally high efficiency
  - Essentially all of the energy taken out of the steam is converted into shaft energy

$$\eta_{first\ law} = \frac{\dot{W}_{shaft}}{\dot{m}_{steam}\left(h_i - h_e\right)} \approx 100\%$$

- Steam turbines operate with only minor “losses”
  - Bearing friction
  - Heat transfer
  - Gland losses

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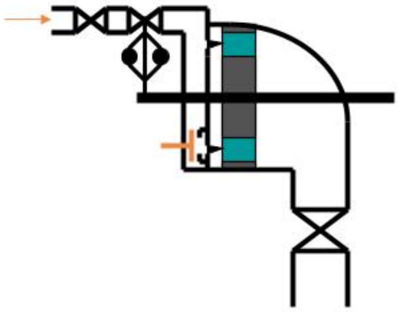
The Perfect Turbine



- Steam turbines are evaluated using the Second Law of Thermodynamics
  - The Second Law of Thermodynamics identifies that *thermal energy* cannot be converted completely into *power*
    - — *Power* can be converted completely into *thermal energy*
- This defines the maximum amount of shaft power that could possibly be produced (based on the laws of physics)
  - This defines a perfect turbine, which would operate isentropically
    - — Isentropic is constant entropy (no losses)
      - No entropy generation

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Isentropic Efficiency

- Steam turbine efficiency is described as isentropic efficiency
  - Essentially all of the energy taken out of the steam is converted into shaft energy

$$\eta_{isentropic} = \frac{Actual\ Work}{Isentropic\ Work} = \frac{\dot{W}_{actual}}{\dot{W}_{isentropic}}$$

$$\eta_{isentropic} = \frac{\dot{m}_{steam}\left(h_{inlet} - h_{exit}\right)_{actual}}{\dot{m}_{steam}\left(h_{inlet} - h_{exit}\right)_{isentropic}} = \frac{\left(h_i - h_e\right)_{actual}}{\left(h_i - h_e\right)_{isentropic}}$$

Isentropic Efficiency

- Steam turbine efficiency is not "like" boiler efficiency
  - Turbine isentropic efficiency is a comparison of the actual turbine operation to that of a perfect turbine operating with the same inlet conditions and outlet pressure
  - Isentropic efficiency is a description of how much mechanical energy is developed from thermal energy
- The steam exiting the turbine contains a significant amount of useful thermal energy

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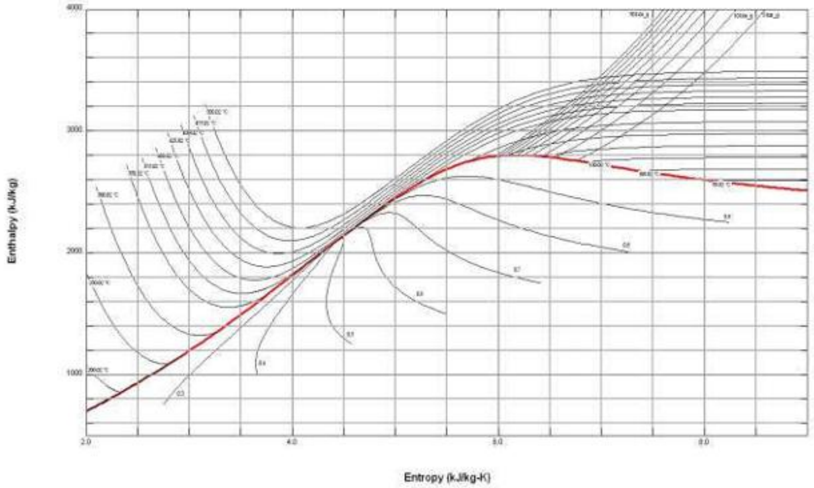
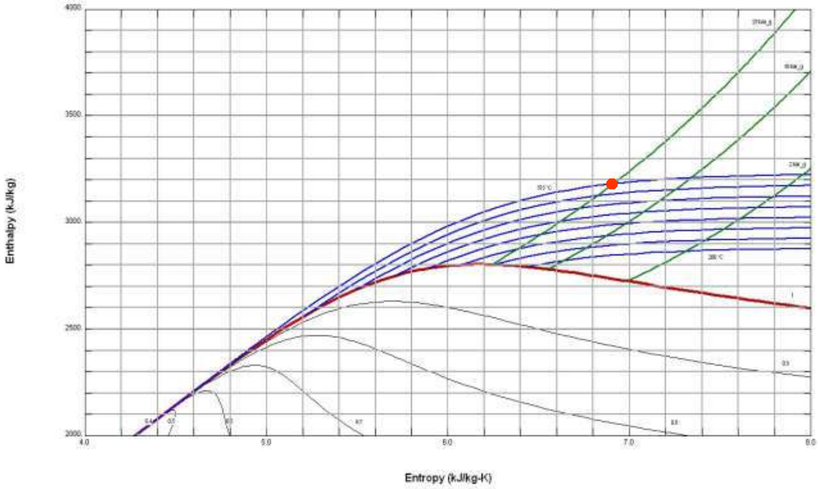
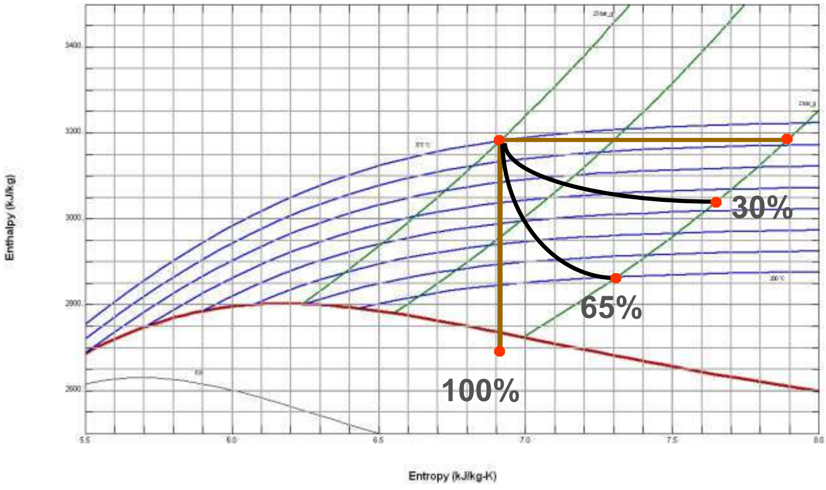


Mollier Diagram



Mollier Diagram



Mollier Diagram – Isentropic Turbine Efficiency

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Typical Steam Turbine Efficiency

$$\eta_{isentropic} = \frac{(h_{in} - h_{out})_{actual}}{(h_{in} - h_{out})_{isentropic}} = 20\% \text{ to } 80\%$$

- Major contributors to isentropic efficiency
  - Turbine design
  - Control valve type
    - Single valve – throttle
    - Multi-valve – flow nozzles
- Will need this information for ANY turbine analysis

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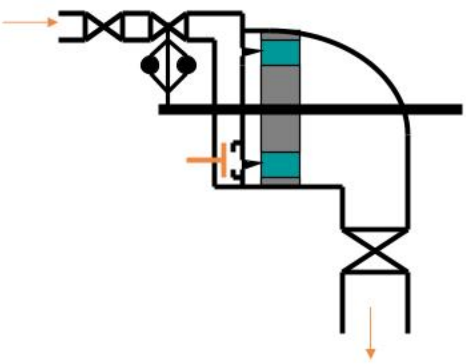
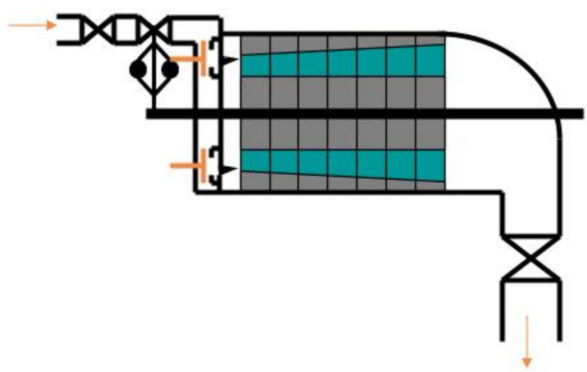
Steam Turbine Efficiency

- Generally, single stage turbines operate with lower isentropic efficiency than multistage turbines
  - Increasing steam path area (diameter) decreases losses
    - Steam exhaust velocity and wall friction decrease
- Single stage turbines are typically more efficient than multistage turbines for small capacity machines

Steam Turbine Efficiency



Single Stage Backpressure Turbine



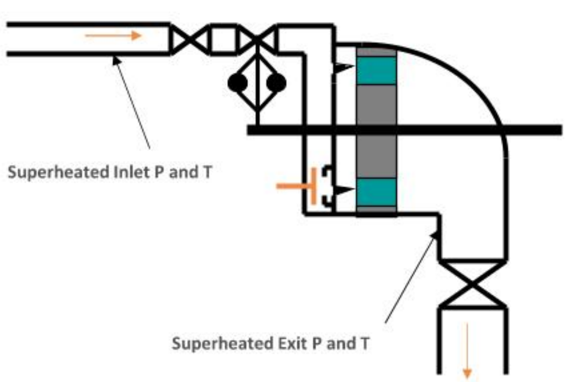
Multistage Backpressure Turbine

Steam Turbine Efficiency

- Three methods of obtaining isentropic turbine efficiency
  - Manufacturer specifications
    - Turbine maps / performance curves
    - Excellent starting point – for new designs also
- Steam inlet and outlet conditions known
  - Superheated inlet along with superheated outlet is the most common and easiest to utilize
  - Will NOT work with saturated outlets (quality < 1)
- Steam inlet conditions and power generation known
  - Typically used for electrical power generation units
  - Mass flow rate of steam will be required
  - Alternate option may exist for direct mechanical driven equipment but with higher uncertainty

Turbine Efficiency from Inlet and Outlet Steam Conditions

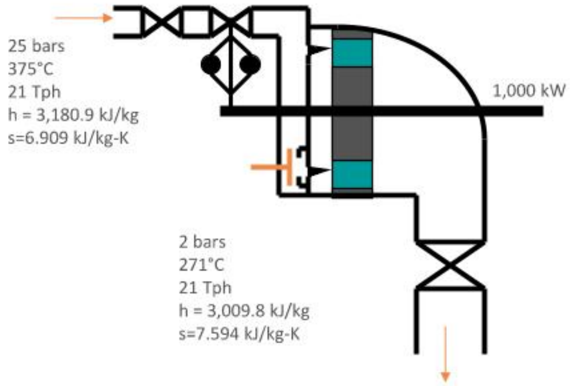
- Method 2
- Turbine performance can be determined from inlet and outlet steam conditions and steam properties associated at those conditions



Steam Turbine Efficiency

- For **superheated steam** conditions at the turbine inlet and outlet
  - Pressure and temperature measurements of superheated steam allow all of the thermodynamic properties to be known

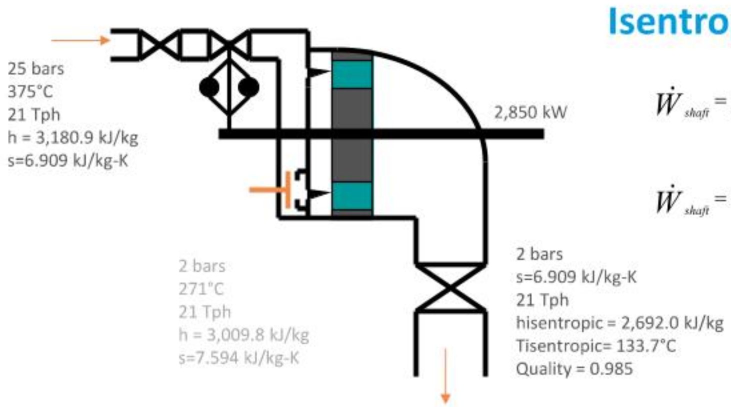
Actual Operating Conditions



$$\dot{W}_{shaft} = \dot{m}_{steam}\left(h_i - h_e\right)_{steam} = \frac{21,000}{3,600}(3,180.9 - 3,009.8)$$

$$\dot{W}_{shaft} = 1,000\ kW = 1,000\ kW\left(\frac{1\ hp}{0.746\ kW}\right) = 1,340\ hp$$

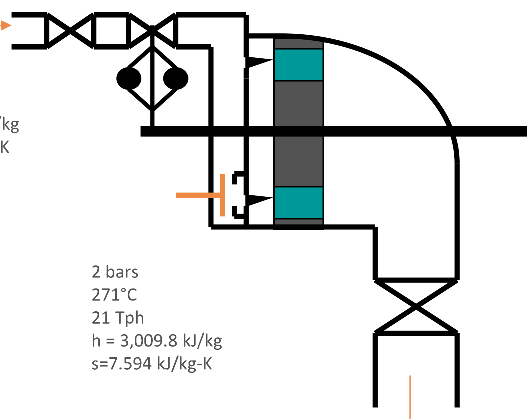
Isentropic Conditions



$$\dot{W}_{shaft} = \dot{m}_{steam}\left(h_i - h_e\right)_{steam} = \frac{21,000}{3,600}(3,180.9 - 2,692.0)$$

$$\dot{W}_{shaft} = 2,850\ kW = 2,850\ kW\left(\frac{1\ hp}{0.746\ kW}\right) = 3,825\ hp$$

25 bars
375°C
21 Tph
h = 3,180.9 kJ/kg
s=6.909 kJ/kg-K

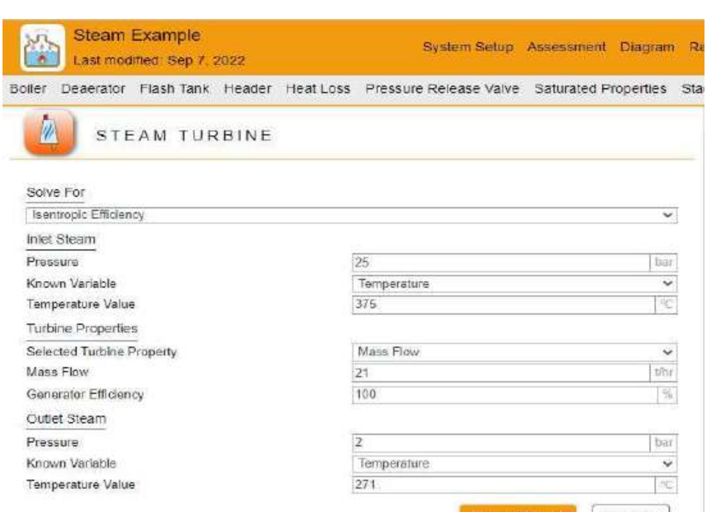


2,850 kW

2 bars
271°C
21 Tph
h = 3,009.8 kJ/kg
s=7.594 kJ/kg-K

2 bars
s=6.909 kJ/kg-K
21 Tph
hisentropic = 2,692.0 kJ/kg
Tisentropic= 133.7°C
Quality = 0.985

$$\eta_{isentropic} = \frac{(h_{inlet} - h_{exit})_{actual}}{(h_{inlet} - h_{exit})_{isentropic}} = \frac{(3{,}180.9 - 3{,}009.8)}{(3{,}180.9 - 2{,}692.0)} = \frac{171.1}{488.9} = 0.35$$



Steam Turbine Calculator - MEASUR

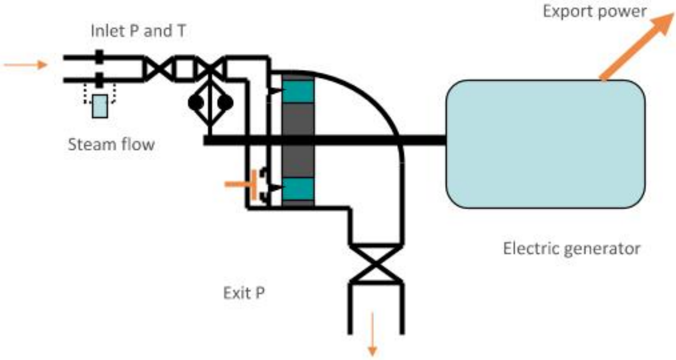
Isentropic Efficiency		35 %	
Energy Out		3.6 GJ/hr	
Generator Efficiency		100 %	
Power Out		999.4 kW	
	Inlet	Outlet Ideal	Outlet
Pressure (bar)	25	2	2
Temperature (°C)	375	133.7	271
Phase	Gas	0.99	Gas
Sp. Enthalpy (kJ/kg)	3,181.9	2,693	3,010.6
Sp. Entropy (kJ/kg-K)	6.911	6.911	7.596
Mass Flow (t/hr)	21	——	21
Energy Flow (GJ/hr)	66.8	——	63.2

Steam Turbine Calculator - MEASUR

Turbine Efficiency from Steam Conditions and Power Production

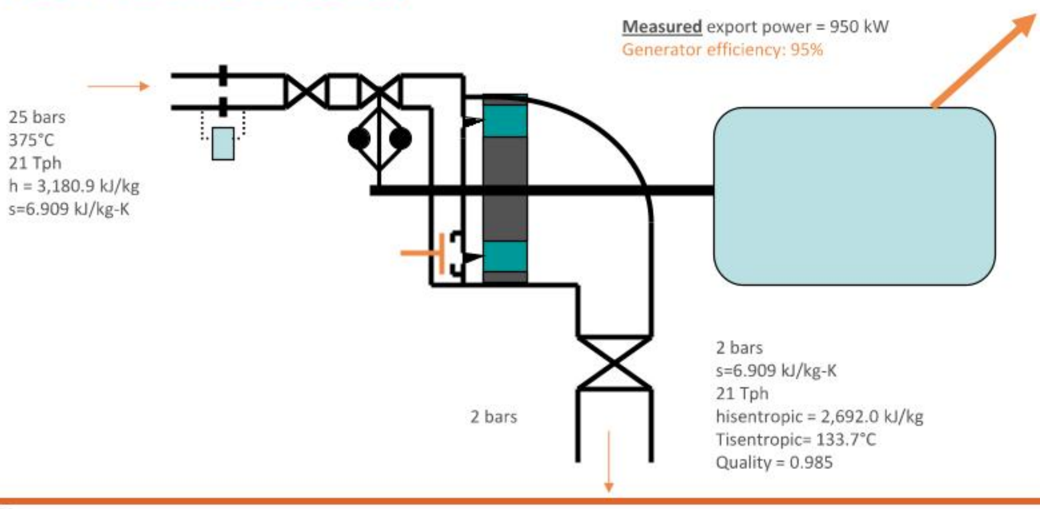
- Method 3
- Turbine performance can be determined from inlet steam properties and power production

Steam Turbine Generator Efficiency



- Steam turbines coupled with electric generators provide an additional mechanism for calculating turbine isentropic efficiency
  - Additional measurements are required to allow the efficiency determination
  - This is typically the only practical method to evaluate condensing turbine efficiency

Steam Turbine Efficiency



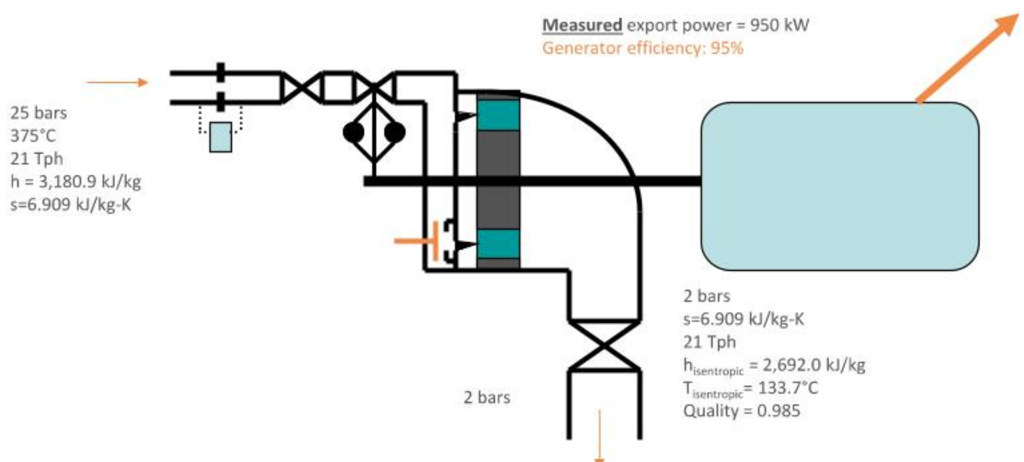
Steam Turbine Efficiency

$$\dot{W}_{generator} = 950\ kW$$

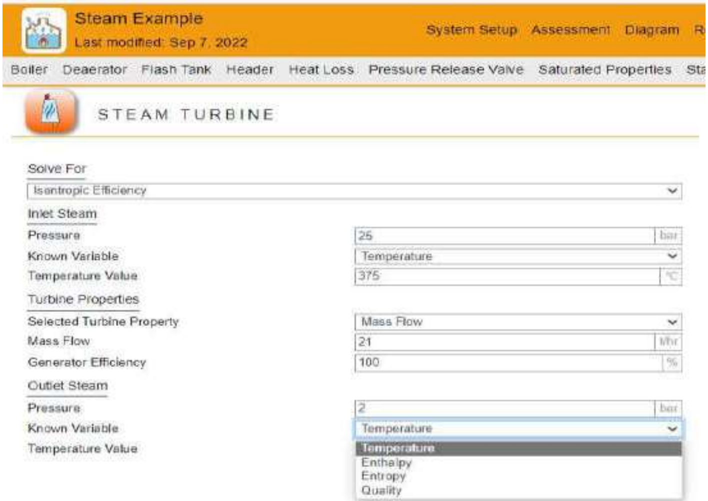
$$\eta_{generator} = \frac{Generator\ Work}{Turbine\ Shaft\ Work} = \frac{\dot{W}_{generator}}{\dot{W}_{turbine}} = \frac{950\ kW}{\dot{W}_{turbine}} = 0.95$$

$$\dot{W}_{turbine} = 1{,}000\ kW$$

$$\eta_{isentropic} = \frac{Actual\ Turbine\ Work}{Isentropic\ Work} = \frac{\dot{W}_{generator}}{\eta_{generator}\dot{W}_{isen}} = \frac{\dot{W}_{gen}}{\eta_{gen}\dot{m}_{st}\left(h_i - h_e\right)_{isen}}$$

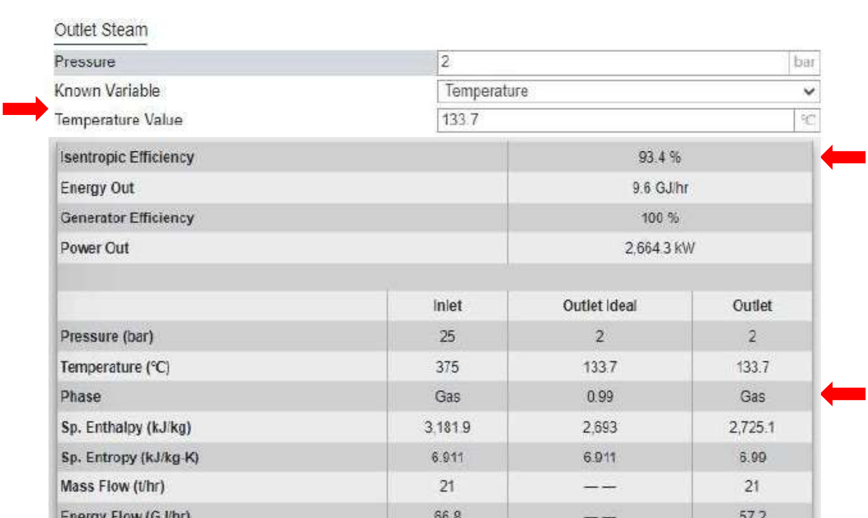


$$\eta_{isentropic} = \frac{950\ kW}{0.95}\frac{3{,}600\ \frac{s}{hr}}{21{,}000\ \frac{kg}{hr}}\frac{1}{\left(3{,}180.9\ \frac{kJ}{kg} - 2{,}692.0\ \frac{kJ}{kg}\right)} = 0.35$$



Steam Turbine Calculator – MEASUR

- If the steam turbine outlet is "saturated" (wet)
- Iterate on the calculator using "quality" to match power generated
- Steam flow will be required



Outlet Steam

Pressure	2	bar
Known Variable	Temperature	
Temperature Value	133.7	°C

Isentropic Efficiency	93.4 %
Energy Out	9.6 GJ/hr
Generator Efficiency	100 %
Power Out	2,664.3 kW

	Inlet	Outlet Ideal	Outlet
Pressure (bar)	25	2	2
Temperature (°C)	375	133.7	133.7
Phase	Gas	0.99	Gas
Sp. Enthalpy (kJ/kg)	3,181.9	2,693	2,725.1
Sp. Entropy (kJ/kg-K)	6.911	6.911	6.99
Mass Flow (t/hr)	21	— —	21
Energy Flow (GJ/hr)	66.8	— —	57.2

Steam Turbine Calculator - MEASUR

Outlet Steam

Pressure	2	bar
Known Variable	Temperature	
Temperature Value	133.65	°C

Isentropic Efficiency	535.9 %
Energy Out	55 GJ/hr
Generator Efficiency	100 %
Power Out	15,282.7 kW

	Inlet	Outlet Ideal	Outlet
Pressure (bar)	25	2	2
Temperature (°C)	375	133.7	133.6
Phase	Gas	0.99	Liquid
Sp. Enthalpy (kJ/kg)	3,181.9	2,693	562
Sp. Entropy (kJ/kg-K)	6.911	6.911	1.673
Mass Flow (t/hr)	21	——	21
Energy Flow (GJ/hr)	66.8	——	11.8

Steam Turbine Calculator - MEASUR

Steam Rate

- Steam rate is an expression used to describe the amount of steam required to produce a specific amount of power
  - Theoretical steam rate is the ideal steam rate
  - Actual steam rate is the real world steam rate

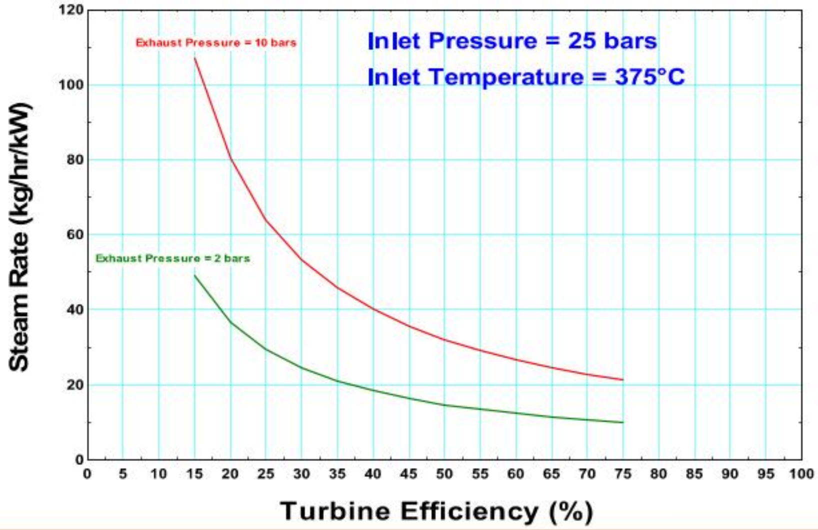
$$Theoretical\ Steam\ Rate = TSR = \frac{\dot{m}_{steam}}{\dot{W}_{isentropic}} = \frac{1}{(h_1 - h_{2\,isen})}$$

$$Actual\ Steam\ Rate = ASR = \frac{\dot{m}_{steam}}{\dot{W}_{actual}} = \frac{1}{(h_1 - h_2)}$$

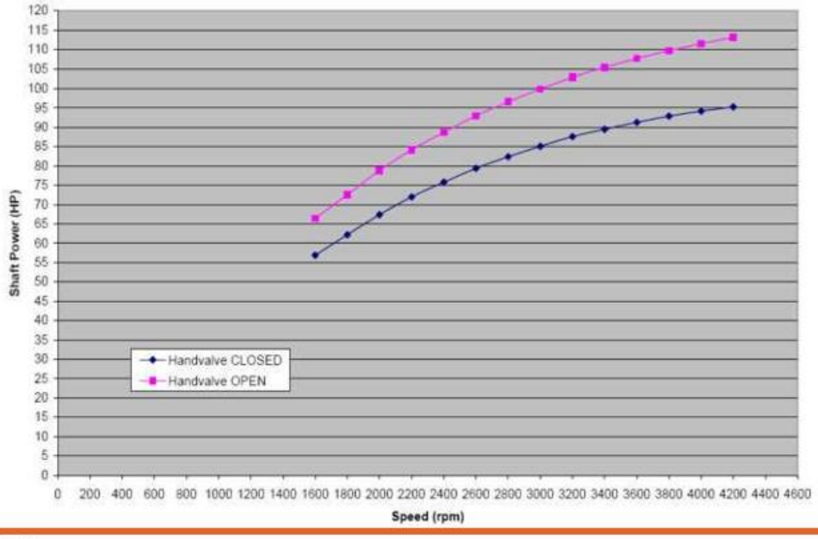
$$\eta_{isen} = \frac{TSR}{ASR}$$

Steam Rate Factors

- Changing turbine inlet or outlet conditions will not impact isentropic efficiency significantly
  - Steam rate will change dramatically if conditions are changed
- Throttling the inlet of a steam turbine will impact the overall isentropic efficiency (valve inlet to turbine outlet)
  - The isentropic efficiency of the turbine will not change significantly (turbine inlet to outlet)
  - Steam rate will change dramatically



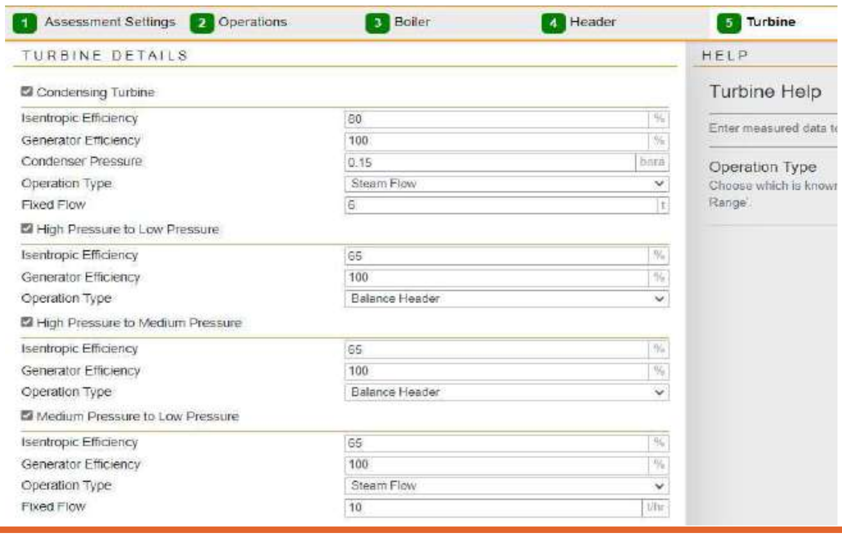
Steam Rate & Efficiency



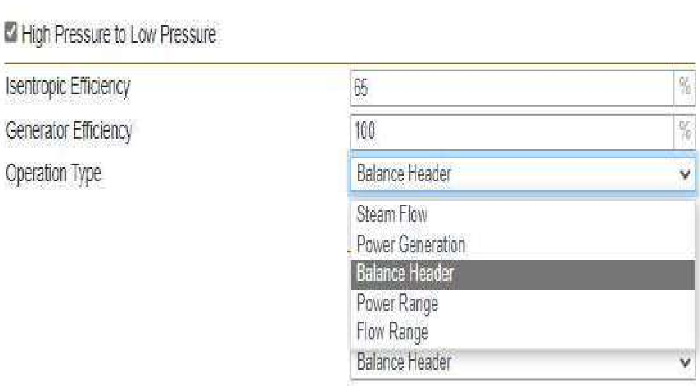
Steam Turbine Speed

MEASUR Steam Turbine Applications

- **Total Site Electrical Demand** is held constant in MEASUR project evaluations
- Power produced by the turbines reduces the **Power Import**
- MEASUR incorporates a maximum of only four turbines
  - HP – LP
  - HP – MP
  - MP – LP
  - HP – Condensing
  - The Impact Turbine must be modeled
- MEASUR allows actual performance to be incorporated into the analysis
  - Turbine efficiency
  - Pressure reducing valve interaction
    - Turbine capacity and control



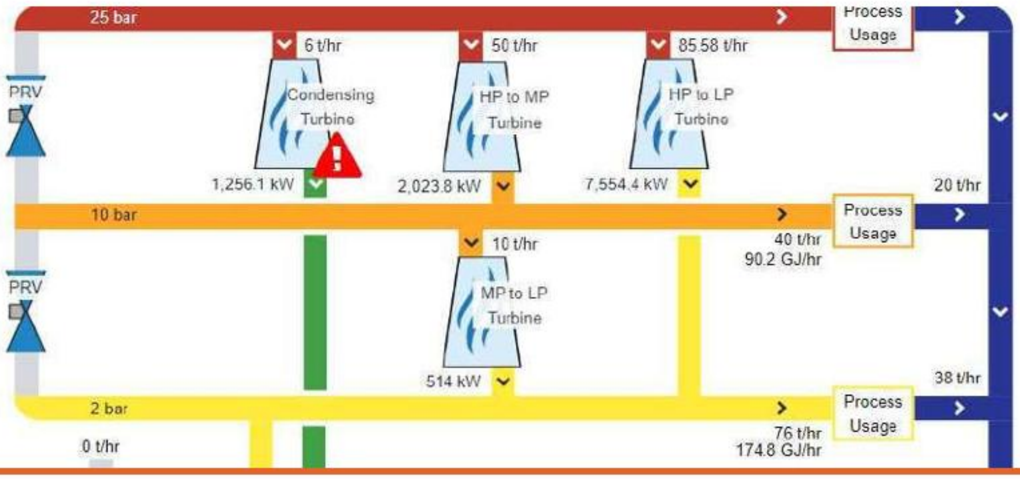
Steam Turbines in MEASUR



Steam Turbines in MEASUR

- Each steam turbine included in the system will need to be configured for efficiency & control options

Steam Turbines Schematically in MEASUR

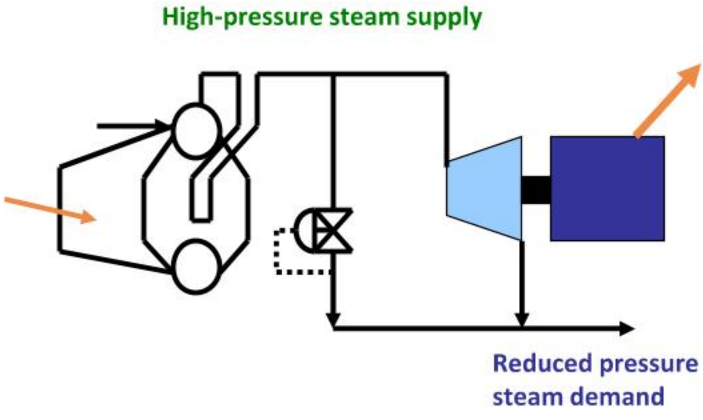


Steam Turbines in MEASUR

- Each steam turbine included in the system will need a steam turbine isentropic efficiency
  - Manufacturers' data
  - Calculated from steam input and output conditions for superheated cases
  - Calculated from power generated and steam input and outlet pressure
    - Generator efficiency needs to be included in the calculations
- Turbine operations are satisfied, then low-pressure demands are satisfied with PRV operation

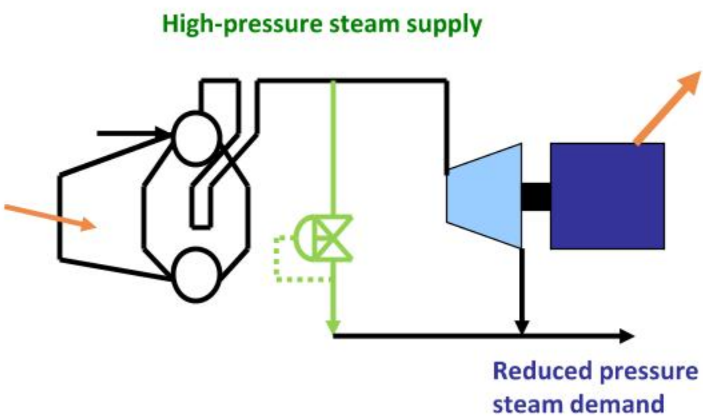
Steam Turbines in MEASUR

- There are three different options to setup the turbine operations
  - Steam flow to the turbine balances the "output" header demand
    - This is also the Default option
  - Turbine set up as fixed operation
    - Fixed steam flow
    - Fixed power generation
  - Turbine setup to operate between minimum and maximum limits
    - Steam flow
    - Power generation
- Turbine NOT operating



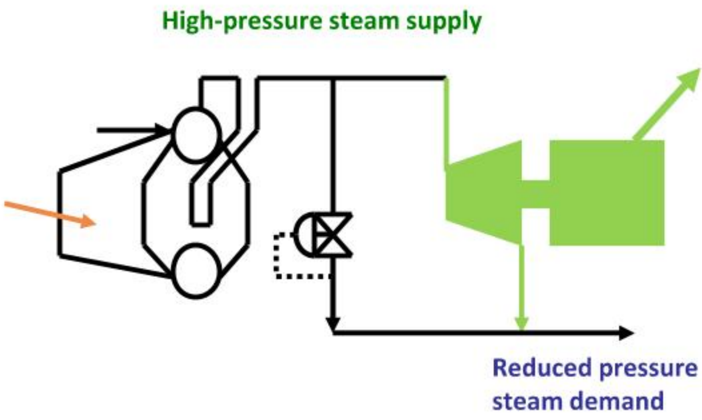
Steam Balance Control

- The MEASUR model must be established to accurately describe the **impact** a change in steam demand (or operating conditions) will have on the system
  - The **impact component** must be established
    - Steam can pass through a turbine
    - Steam can pass through a pressure reducing valve



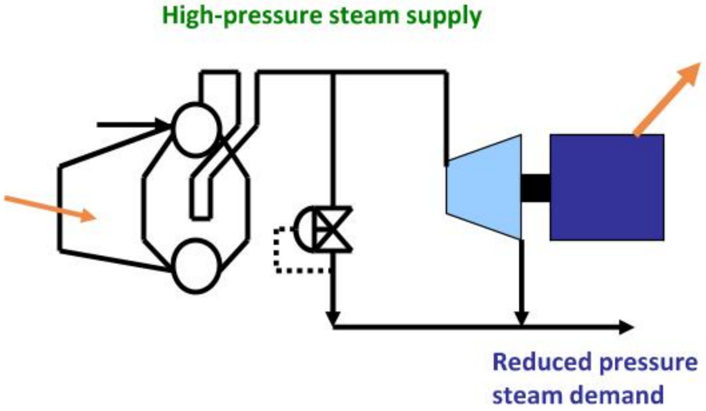
Turbine Control of Steam Balance

- Turbine balances reduced-pressure header
  - The capacity of the turbine is limitless
  - Any change in low-pressure steam demand will result in a change in steam flow through the turbine



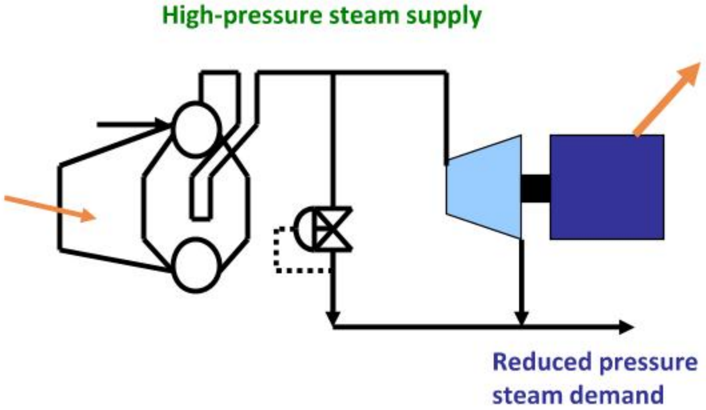
Fixed Turbine – PRV Steam Balance Control

- Turbine is operating based on fixed conditions
  - Steam flow cannot vary through the turbine
  - Any change in low-pressure steam demand will result in a change in steam flow through the PRV
  - Process turbines are typically modeled in this manner



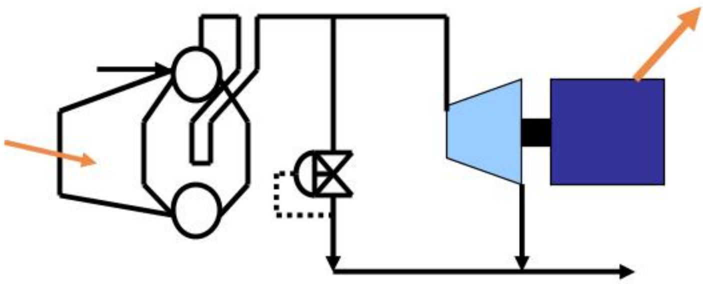
Maximum-Minimum Steam Balance Control

- The turbine can be forced to operate between a minimum and maximum steam flow
  - The PRV will supply additional steam if the turbine capacity limit is reached
  - This provides a realistic limitation based on the capacity of the turbines



Turbine On-Off Control

- The turbine can be turned "on" in the Base model and "off" in the Assessment model
  - The turbine can be turned "off" in the Base model and "on" in the Assessment model



Backpressure Turbine Modeling – Example System

- Open the 3-Header Example System Model and set up the HP-LP turbine with the following configuration
  - Steam turbine flow of ~21.0 Tph
  - Turbine isentropic efficiency = 35%
- Model the economic impact of saving 1 Tph HP and 1 Tph LP steam

Opening a SAVED MEASUR File

- Open MEASUR – Installed or Online version
- Click on "View Assessments"
- The Assessment may already be there on the Dashboard – Click on it

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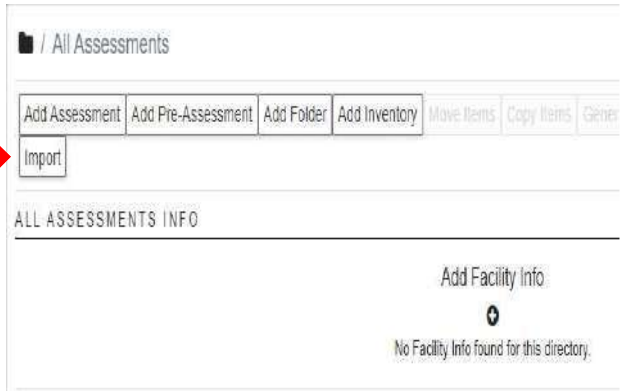

Opening a SAVED MEASUR File

- If the Assessment is NOT there on the Dashboard, then click on “Import” and locate the .json file where the assessment was stored
- For Online version – Downloads folder is default location for file storage

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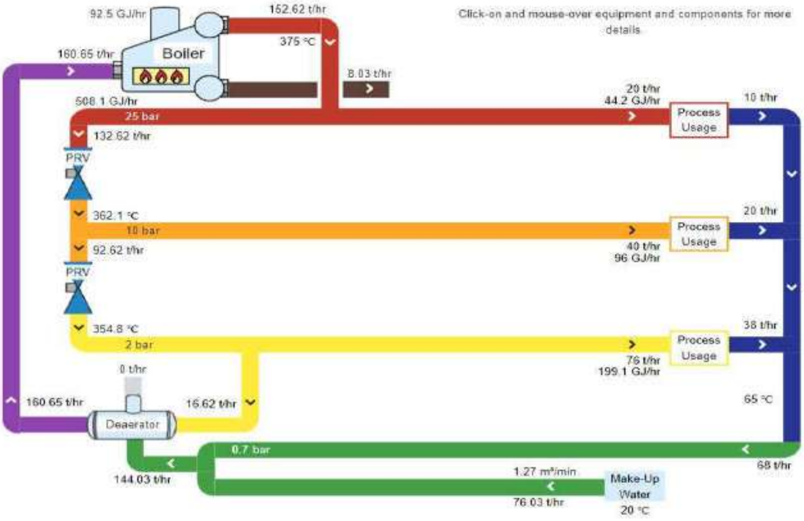


ReCheck Base Model

STEAM SYSTEM SUMMARY

Steam Generated
152.6 t/hr
Total Operating Cost
$116,097,582

CO_2 Emissions (tonne CO_2/yr)	
Emissions From Fuel	223,845.22
Emissions From Selling Electricity	0
Emissions From Change in Electricity Imports	0
Total Emissions	223,845.22

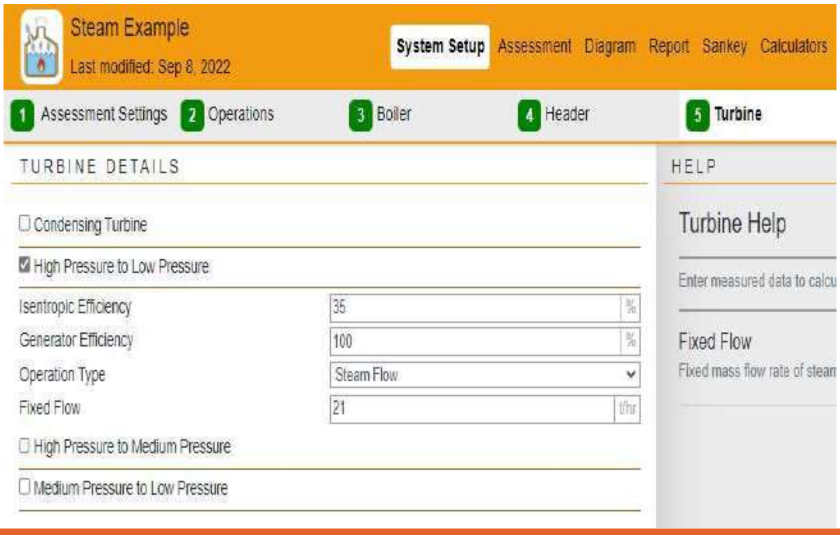
Fuel	
Boiler Fuel Use	4,451,088.07 GJ/yr
Boiler Fuel Cost ($)	$111,277,202

Electricity	
Electricity Generated	0 kW
Electricity Imported	5,000 kW
Electricity Cost ($)	$4,380,000

Make-Up Water	
Make-Up Water Required	667,242.79 m³
Make-up Water Cost ($)	$440,380

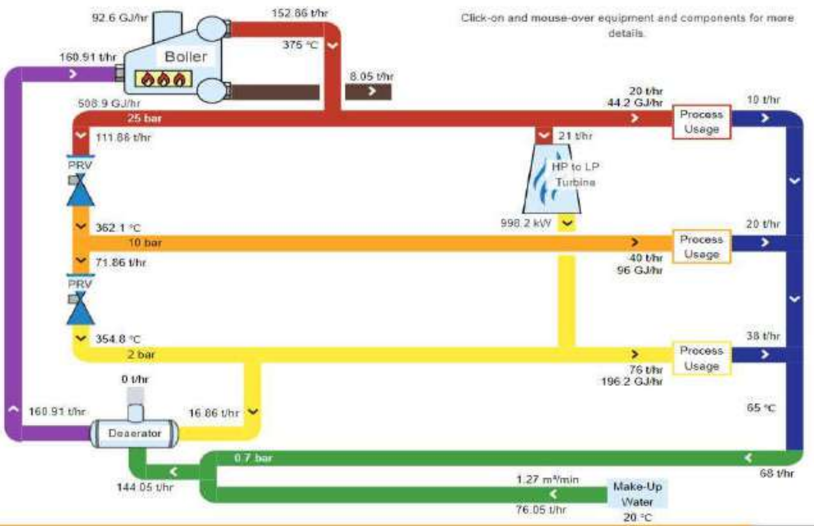
Example System

- Do we agree with all these numbers?
- If yes, which ones do we agree?
- If no, which ones do we NOT agree?



Example System

- Go to Section 5 - “Turbine”
- Check pull-down menu for Operation-type



Example System Model

Turbine Impact Example Results

MARGINAL STEAM COST

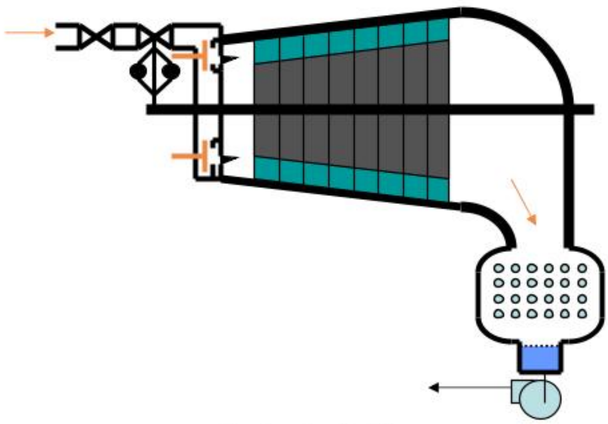
High Pressure	$93.88 /t
Medium Pressure	$93.88 /t
Low Pressure	$93.73 /t

$$Savings_{1Tph\_HP} = 1.0 \times 8{,}760 \times 93.88 = \$822{,}389$$

$$Savings_{1Tph\_LP} = 1.0 \times 8{,}760 \times 93.73 = \$821{,}075$$

Backpressure Turbine Economics

- Most industrial systems require thermal energy (not mass flow of steam)
- The turbine will extract energy from the steam and convert it into shaft energy
  - The steam will exit the turbine with a reduced temperature
- The result will be an increased mass flow of steam required to satisfy the thermal demand



Condensing Turbine

Condensing Steam Turbines

- Condensing steam turbines often operate with a discharge condition of saturated steam
  - Isentropic efficiency is typically determined by
    - — Generator output, steam conditions, and steam flow
    - — Estimated by manufacturer's data

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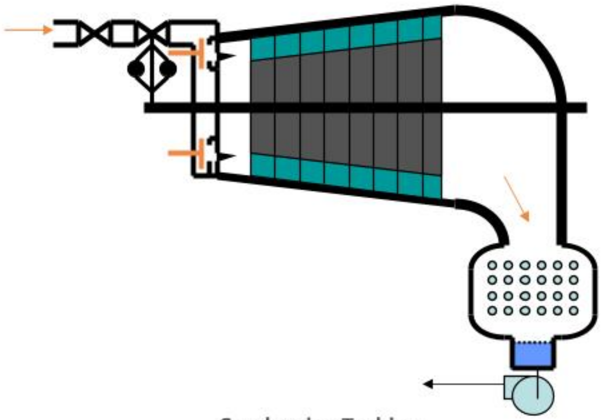
Condensing Steam Turbines



Condensing Turbine

- Discharge pressure has a big effect on power production
  - Several different units are available in MEASUR
  - Be careful when selecting the vacuum pressure units
  - They can be different than header pressure units
- Condensing turbines are used for
  - Large amount of power generation
  - Driving large mechanical equipment

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Condensing Steam Turbines in MEASUR

- Condensing steam turbine(s) need to be set up in the same way as backpressure steam turbines but need one additional input
  - Condenser pressure (vacuum conditions)
- Information on control mechanism is also required

Condensing Steam Turbines in MEASUR

- Condensing turbines have two modes of operation
  - Fixed power generation
    - Most process driven equipment operations will have this configuration
      - 100% generator efficiency
    - When connected to a generator for power generation
      - Use generator efficiency as provided by manufacturer
  - Fixed steam flow
    - Maybe observed in plants which have a lot of waste heat to be recovered
    - Balancing the steam system and eliminating steam venting from the headers

Condensing Steam Turbines in MEASUR

- Condensing turbine isentropic efficiency is required
  - Manufacturers' data
  - Calculated from steam inlet, flow and power generated
- Condensing turbine outlet (discharge) pressure
  - Can be provided in either of the four units
  - Equivalent to surface condenser pressure

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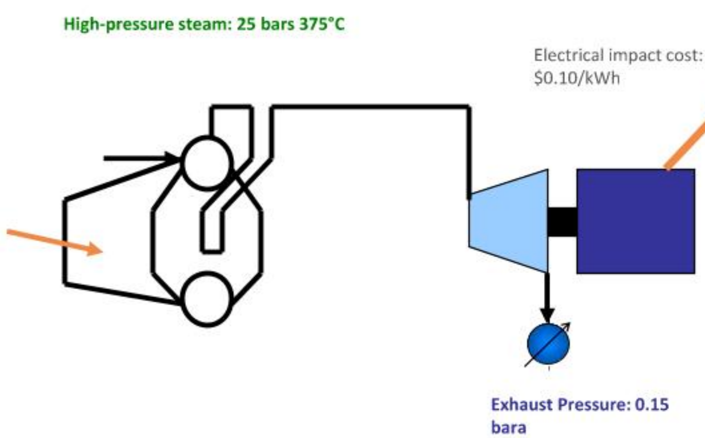
Condensing Turbine - Example System



- Open the 3-Header Example System Model and set up the condensing turbine with the following configuration
  - Fixed power generation = 950 kW
  - Generator efficiency = 95%
  - Turbine isentropic efficiency = 80%

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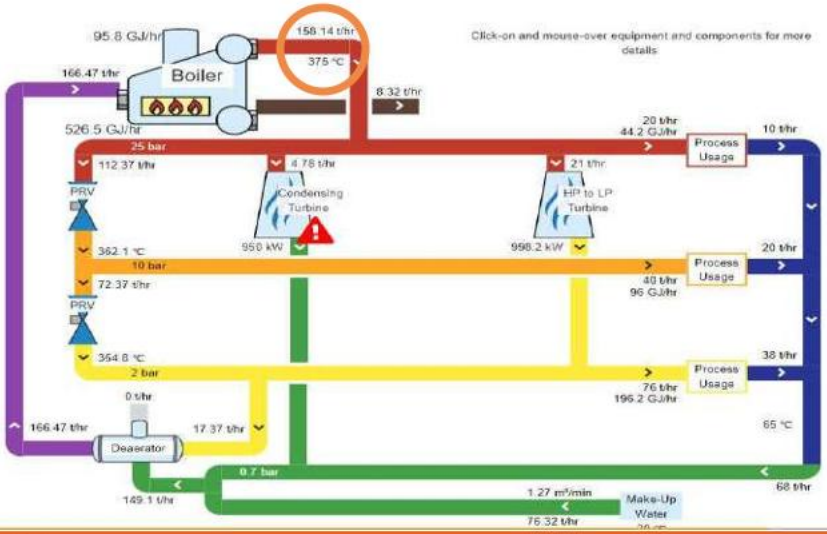
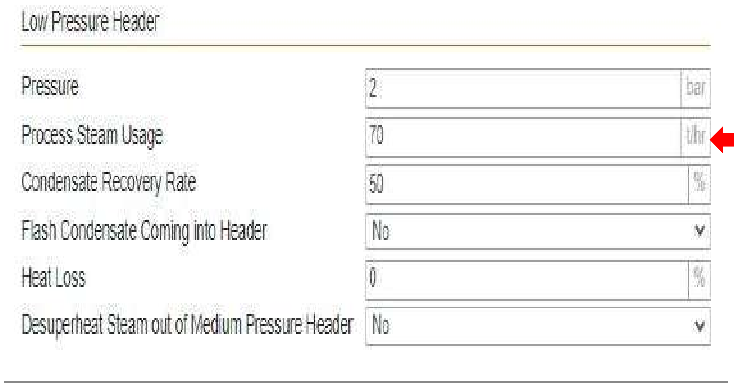
Condensing Turbine Example Results





Condensing Turbine Example Results

- Make a small change in the Base Model input
  - Change Low Pressure header process steam usage to 70 Tph

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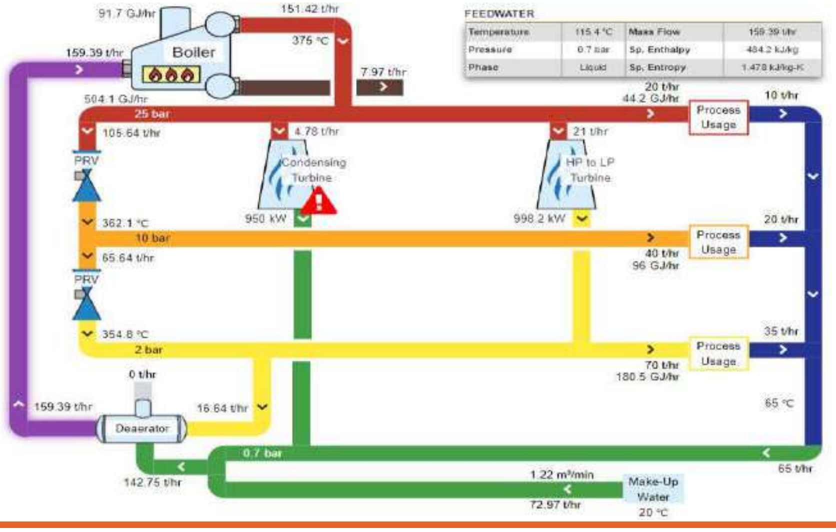


Condensing Turbine Example Results

Condensing Turbine Example Results

COST SUMMARY

Power Balance	
Generation	1,948.2 kW
Demand	6,948.2 kW
Import	5,000 kW
Unit Cost	$0.10 /kWh
Total $/yr	$4,380,000

Fuel Balance	
Boiler	504.12 GJ/hr
Unit Cost	$25.00 /GJ
Total $/yr	$110,402,099

Make-Up Water	
Flow	1.22 m³/min 640,361.2 m³
Unit Cost	$0.66 /m³
Total $/yr	$422,638

Total Operating Cost
$115,204,737

MARGINAL STEAM COST

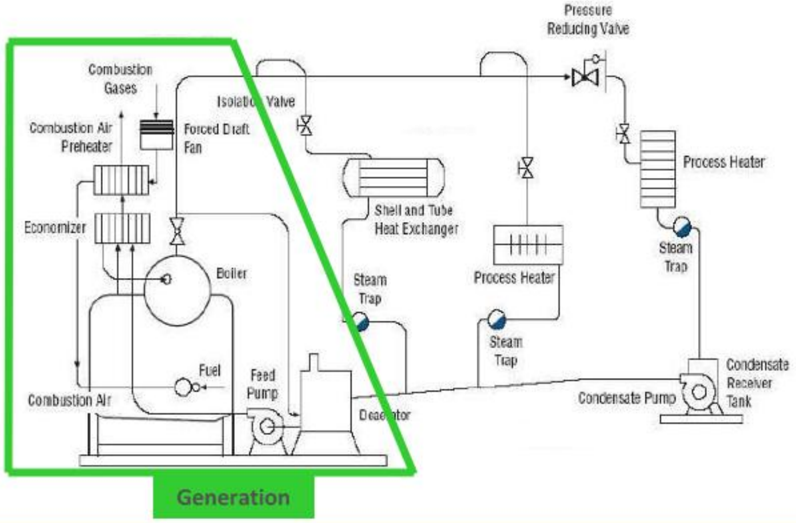
High Pressure	$93.89 /t
Medium Pressure	$93.89 /t
Low Pressure	$93.72 /t

Example System Model

- All the model “Inputs” are complete
- The 3-header model
  - Closely represents steam flows and steam balance on the headers as would be in the operating case
  - Accurately models the impact (marginal) steam costs of the system
  - DOES NOT represent total utility costs, emissions, etc.
    - NOTE: Impact fuel is used for modeling
  - Is ready to be used to accurately reflect economic impacts of energy saving and optimization opportunities in the steam system
- Make sure it is SAVED!

Section 5: Steam System Optimization – Generation

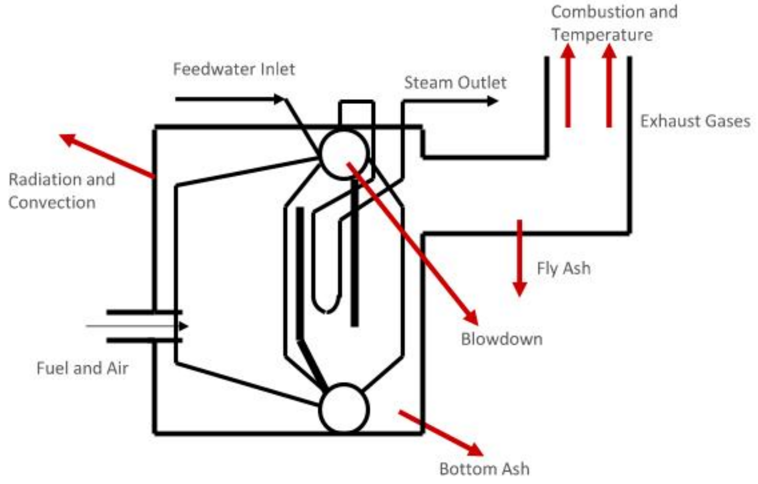
- Boiler Efficiency Improvement
- Blowdown Management
- Blowdown Energy Recovery
- Feedwater Economizers
- Combustion AirPreheaters
- Excess Air Control
- Fuel Switching
- Hands-On Student Exercises



Steam System Optimization – Generation

Source: US DOE Steam BestPractices Program

Boiler losses



Source: US DOE Steam BestPractices Program

- Boiler efficiency can also be determined in an indirect manner by determining the magnitude of the losses
  - Primary losses are typically
    - Shell loss
    - Blowdown loss
    - Stack loss

$$\eta_{boiler} = 100 - Losses$$

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

Shell Losses

- Full-load radiation and convection losses are typically:
  - Less than 1.0% for water-tube boilers
  - Less than 0.5% for fire-tube boilers
- Shell loss *percentage* increases as boiler load decreases because *shell loss magnitude is essentially constant*
  - Shell loss of ~0.5% at full-load will become ~2.0% at quarter-load
  - The primary opportunity in this area is to reduce the number of boilers in operation to reduce the total site shell loss
    - — Stack loss impacts must be considered
- Reducing steam demand will NOT result in any change in shell loss….. Unless a boiler is shut down!

Key Points / Action Items

1. Search for "hot spots"
2. Measure boiler surface temperatures
   - Infrared thermography
   - Typical surface temperature should range between 55°C and 70°C
3. Repair refractory
4. Monitor surface cladding integrity
5. Reduced boiler load can present an opportunity
   - Minimize number of operating boilers

Blowdown Management

- Water quality must improve as steam pressure increases
- Most facilities require makeup water softening as a minimum
- Higher pressure systems may require dealkalization, demineralization, or reverse osmosis treatment of makeup water
- High quality water systems may have less than 1% blowdown
  - Low quality water systems may have as much as 10% blowdown
- Additional condensate recovery will typically allow the blowdown rate to be reduced

Blowdown Management

- Blowdown amount is primarily dependent on:
  - Water quality
  - Boiler operating pressure
- Blowdown management typically takes the following forms
  - Makeup water quality improvement
  - Improved blowdown control
  - Heat recovery
  - Increased condensate recovery
- Blowdown management begins with measurement
  - Typically, blowdown amount is estimated from boiler water chemical analysis

Source: US DOE Steam BestPractices Program

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Options for Blowdown Energy Savings

- Reduce boiler blowdown
  - This will reduce energy in the blowdown stream proportionately
  - But water quality will need to be improved significantly
    - Economic considerations
    - Infrastructure considerations
- Implement energy recovery equipment
  - Capture almost all the blowdown energy
  - No impact on water treatment, may actually help
  - System effects need to considered, especially in a cogeneration plant
- A combination of the above two options

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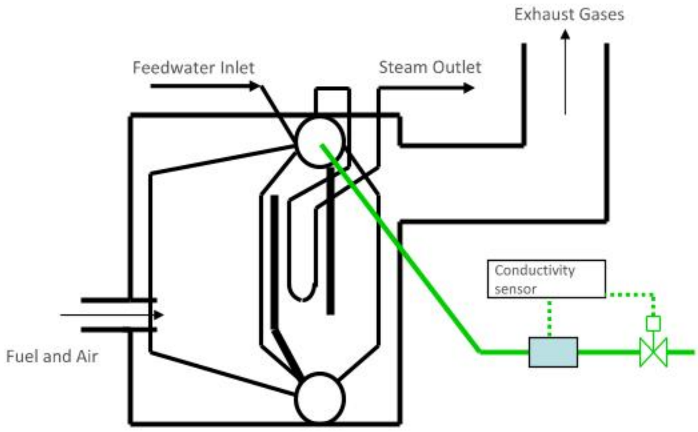
Blowdown Control

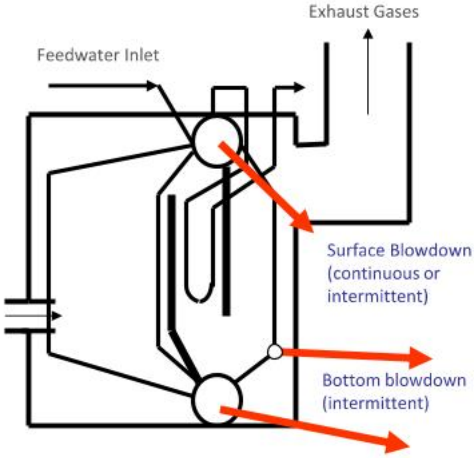
- Primary control of continuous blowdown is typically based on boiler water conductivity
- Conductivity must be correlated to actual water quality through specific analysis



Blowdown Control

Blowdown Loss

- A change in the boiler blowdown amount of all of the boilers will generally reduce the impact fuel consumption
- Economic analysis will require either multiple models for different fuels
  - Blended fuel cost may provide a good ball-park estimate
- Increased condensate return will typically allow the blowdown rate to be reduced



MEASUR - Reduce Boiler Blowdown

- Blowdown is required based on water quality
- What would allow a reduction in boiler blowdown?
  - Cleaner feedwater
    - Increased condensate return
    - Additional makeup water conditioning
    - Condensate polishing
    - Change in water treatment
  - Continuous versus intermittent blowdown

Reduce Boiler Blowdown

- Open the 3-header MEASUR Base Model
- Use the 3-header MEASUR Example System model and quantify the total economic impact of reducing boiler blowdown from 5% to 2%. This reduction in blowdown is possible with an improvement (upgrade) in the water treatment system

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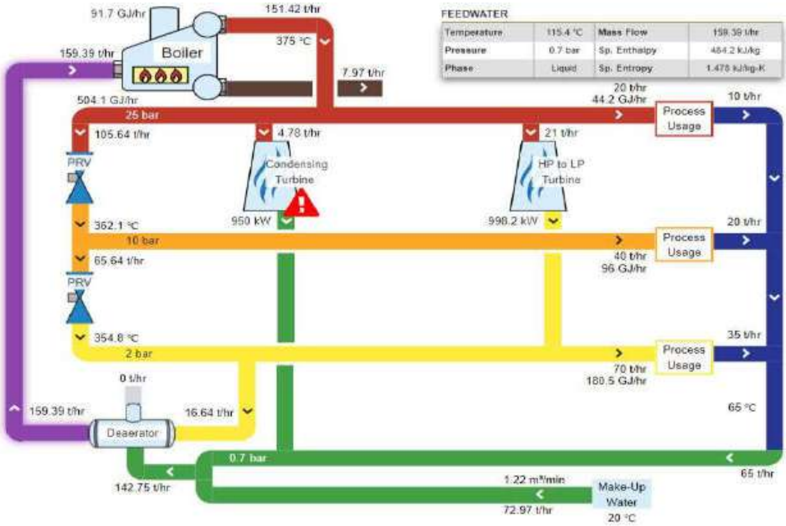

Example System (Base Model) Results

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Example System (Base Model) Results

COST SUMMARY

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MARGINAL STEAM COST

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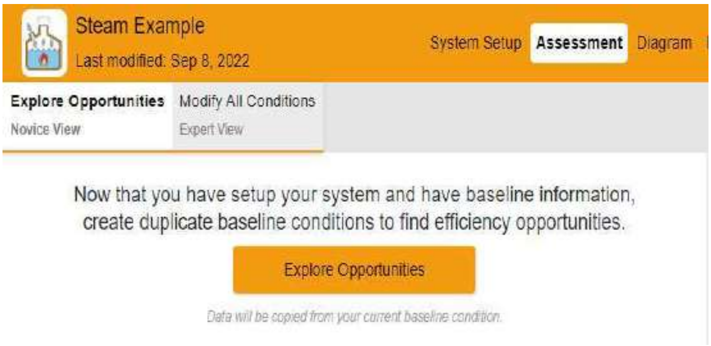
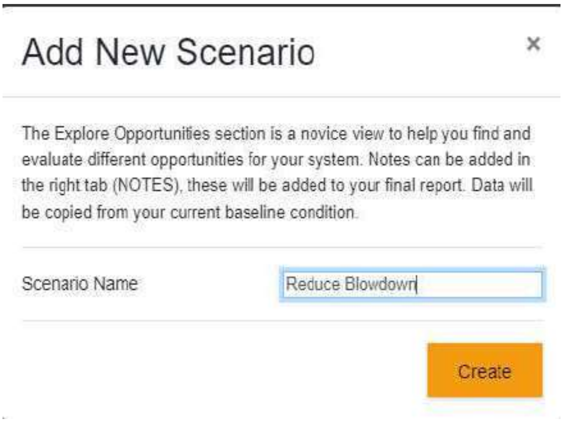
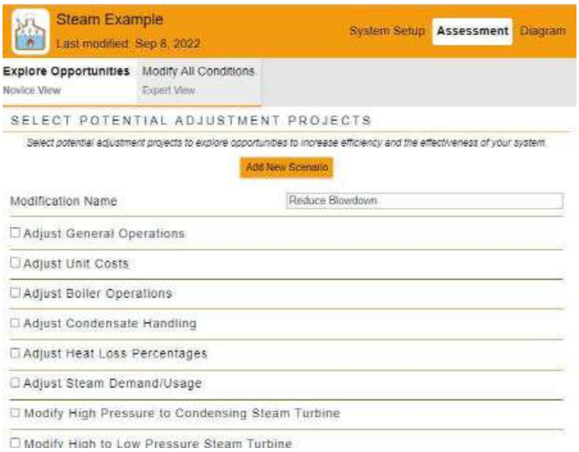
Example System Assessment

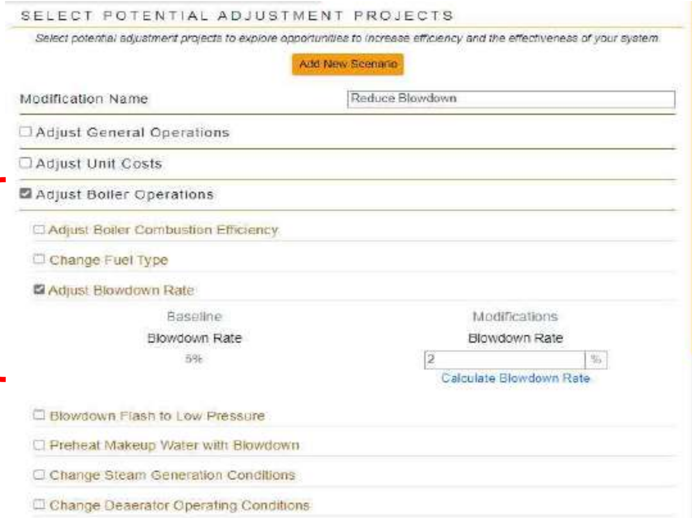


- There are two options
  - Novice view
  - Expert view
- Both will lead to the same result

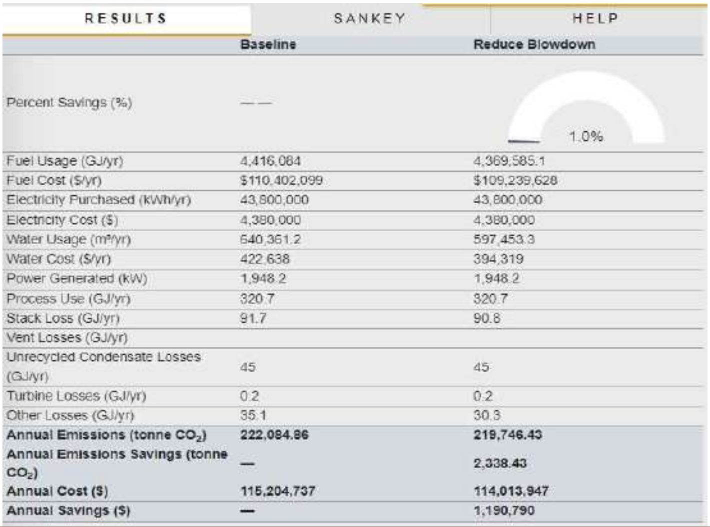
Example System Assessment – Novice View







Example System Assessment – Reduce Blowdown



RESULTS | SANKEY | HELP

	Baseline	Reduce Blowdown
Percent Savings (%)	— —	1.0%
Fuel Usage (GJ/yr)	4,416,084	4,369,585.1
Fuel Cost ($/yr)	$110,402,099	$109,239,628
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m^3/yr)	640,361.2	597,453.3
Water Cost ($/yr)	422,638	394,319
Power Generated (kW)	1,948.2	1,948.2
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	91.7	90.8
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	30.3
Annual Emissions (tonne CO_2)	**222,084.86**	**219,746.43**
Annual Emissions Savings (tonne CO_2)	**—**	**2,338.43**
Annual Cost ($)	**115,204,737**	**114,013,947**
Annual Savings ($)	**—**	**1,190,790**

Example System Assessment – Reduce Blowdown

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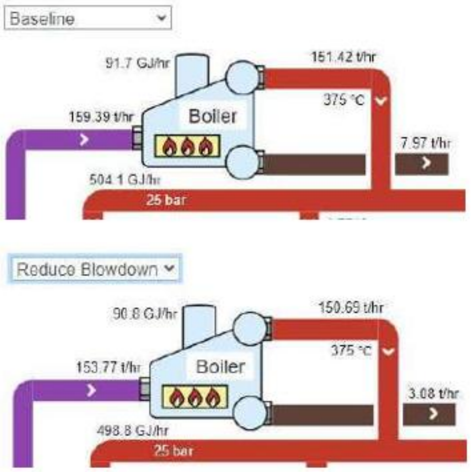

Reduce Boiler Blowdown

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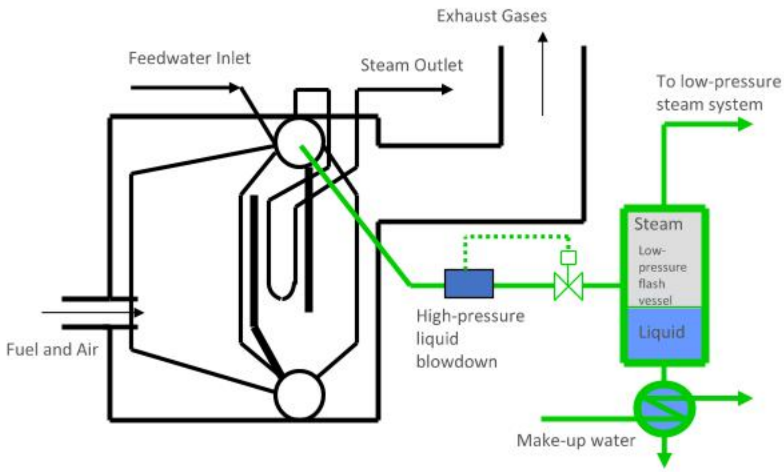
Caution - Reduce Boiler Blowdown

- Be careful of the energy savings, costs and emission results
- Multiple boilers require individual boiler modeling for blowdown reduction opportunities
  - Each fuel and boiler separately imparts energy to the individual boiler's feedwater
- IMPACT fuel and analysis breaks down in this specific improvement opportunity
- Using a blended fuel cost and boiler efficiency may be a better estimate for this opportunity

Blowdown Energy Recovery



Source: US DOE Steam BestPractices Program

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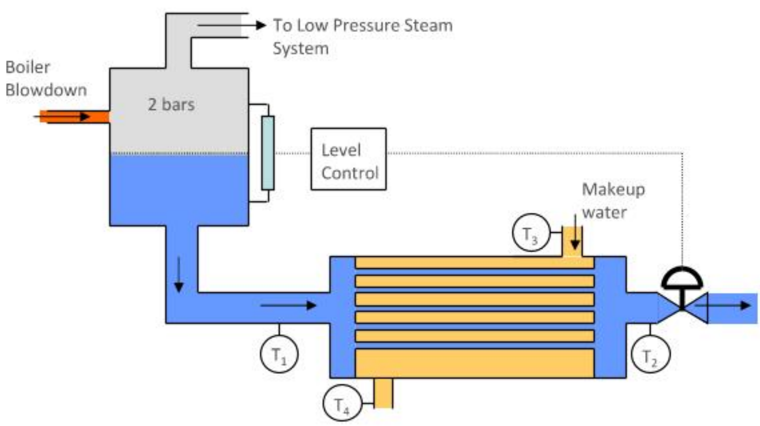
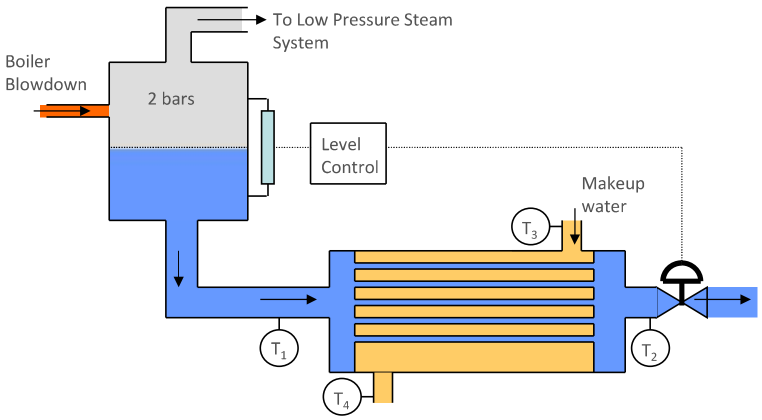
Blowdown Energy Recovery



- 1.6% of the total fuel energy
- Impact fuel ~$1,800,000/yr
  - This loss can be **eliminated**

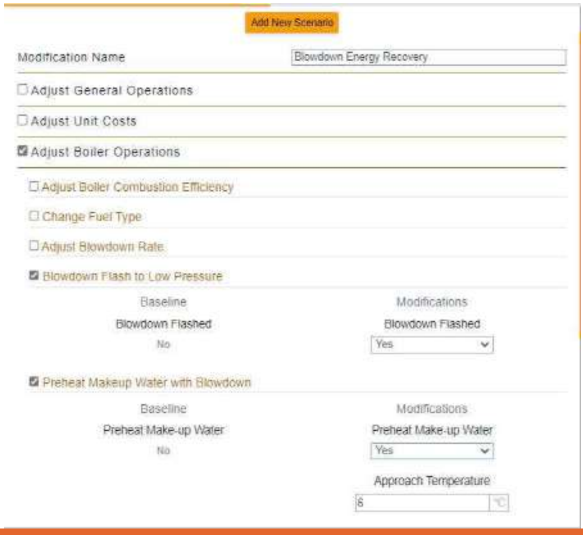
Source: US DOE Steam BestPractices Program



MEASUR Assessment Model

- Add a blowdown flash tank
- Add a heat recovery exchanger

Source: US DOE Steam BestPractices Program



MEASUR Assessment - Blowdown Energy Recovery

MEASUR Assessment - Blowdown Energy Recovery

	Baseline	Blowdown Energy Recovery
Percent Savings (%)	— —	2.0%
Fuel Usage (GJ/yr)	4,416,084	4,342,966.6
Fuel Cost ($/yr)	$110,402,099	$108,574,166
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m³/yr)	640,361.2	627,178.4
Water Cost ($/yr)	422,638	413,938
Power Generated (kW)	1,948.2	1,948.2
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	91.7	90.2
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45.1
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	28
Annual Emissions (tonne CO_2)	**222,084.86**	**218,407.79**
Annual Emissions Savings (tonne CO_2)	**—**	**3,677.07**
Annual Cost ($)	**115,204,737**	**113,368,104**
Annual Savings ($)	**—**	**1,836,633**

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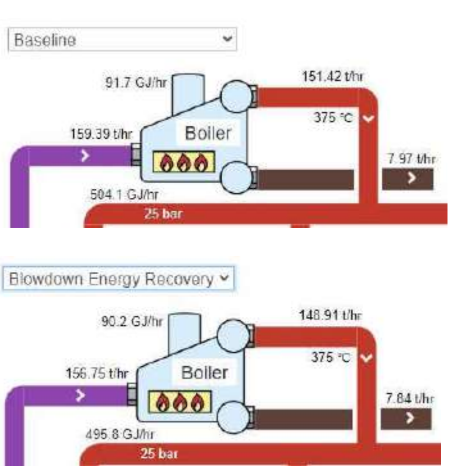
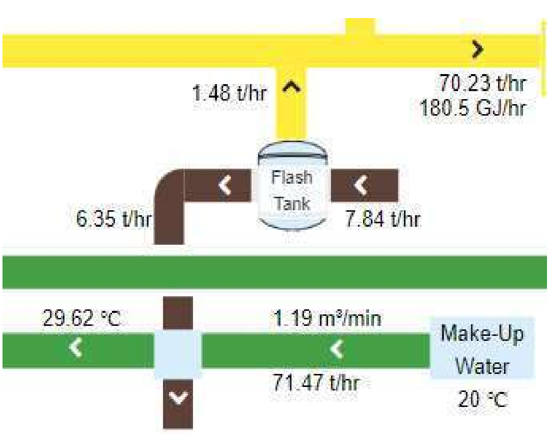
MEASUR Assessment - Blowdown Energy Recovery



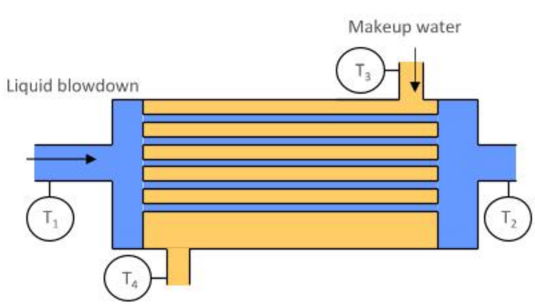


Blowdown Energy Recovery

Blowdown / Make up Water Heat Exchanger

Blowdown Flash Tank

Heat Exchanger Caution



- The blowdown stream presents a significant fouling potential (even in a cooling environment)
- Co-current heat exchange may also be a good option
- The capability of cleaning the heat transfer surfaces of blowdown heat exchangers must be provided
  - Straight tube with blowdown on the tube side
  - Plate and frame

Source: US DOE Steam BestPractices Program

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Blowdown Change with Heat Recovery

- The impact of reducing blowdown is minimized when blowdown heat recovery equipment is in place
  - Blowdown rate can be increased to protect the boiler and the energy cost at the site will not be significantly impacted

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Key Points / Action Items

1. Estimate amount of blowdown using boiler and feedwater conductivities
2. Quantify the boiler and system-level energy loss due to blowdown
3. Evaluate installation of an automatic blowdown controller
4. Evaluate and install flash steam and heat recovery equipment
5. Work closely with plant’s water chemists to maintain and manage appropriate blowdown

Stack Losses

- Stack losses are the largest of the boiler losses
- Stack losses are made up of two parts and defined as
  - Temperature losses
  - Combustion losses
- Combustion analysis is the method generally used to determine stack losses

Boiler Efficiency Improvement Projects

- MEASUR boiler efficiency is primarily dictated by stack loss
  - Real-world boiler efficiency is primarily dictated by stack loss
  - Primary stack loss factors
    - Exhaust temperature
    - Excess air

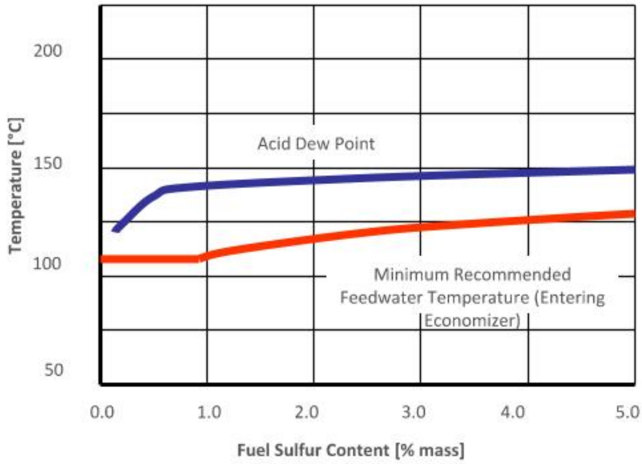
Flue Gas Temperature Loss

- A significant amount of energy resides in the flue gas
  - The temperature of the flue gas indicates the energy content
- The most common factors influencing flue gas temperature are presented are:
  - Boiler design
  - Fuel
  - Availability of heat recovery equipment
    - Feedwater economizers
    - Combustion air-preheaters
  - Failed flue gas component – baffle
  - Fireside or waterside fouling
  - Boiler load

Energy Recovery Components

- A feedwater economizer recovers energy from the flue gas to the boiler feedwater through a heat exchanger
- A combustion air preheater recovers energy from the flue gas to the combustion air
  - Solid fuel boilers are more likely to have these components to aid in combustion by pre-drying the fuel

Flue Gas Temperature Limitations

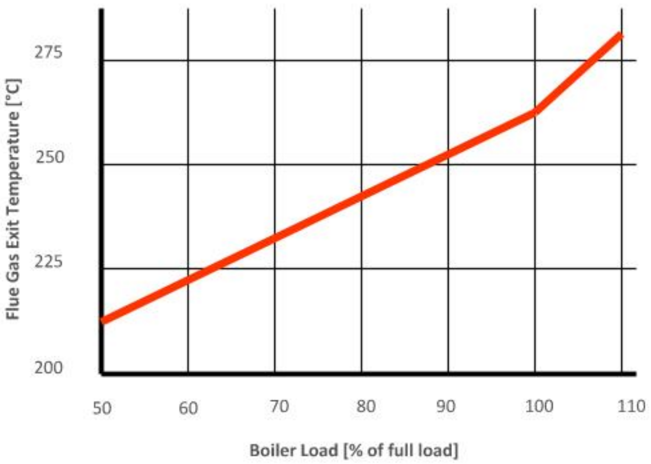


- Flue gas temperature is maintained above the dew point of acidic components
  - Fuels containing sulfur produce sulfuric acid
  - All hydrocarbon fuels can produce carbonic acid

Source: US DOE Steam BestPractices Program

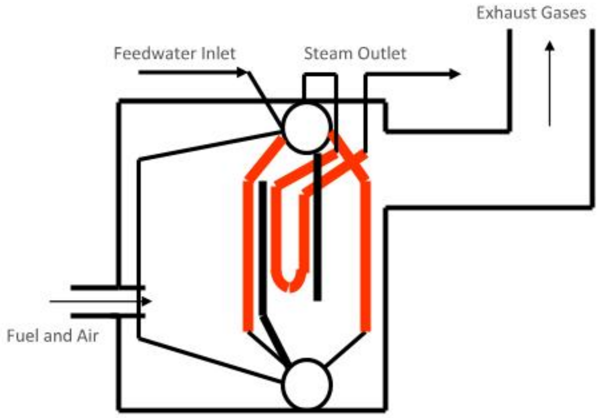
Condensing Economizers

- Condensing economizers can improve boiler efficiency more than 10% in comparison to conventional boilers
  - Final flue gas temperature can approach 30°C
  - Indirect units can heat streams to 90°C
  - Direct units can heat streams to 70°C
  - A significant amount of relatively *low-temperature energy* is recovered
  - Equipment is limited to *clean fuels*
    - Natural gas
    - Light fuel oil



Boiler Load

- Flue gas exhaust temperature typically increases as boiler steam production increases

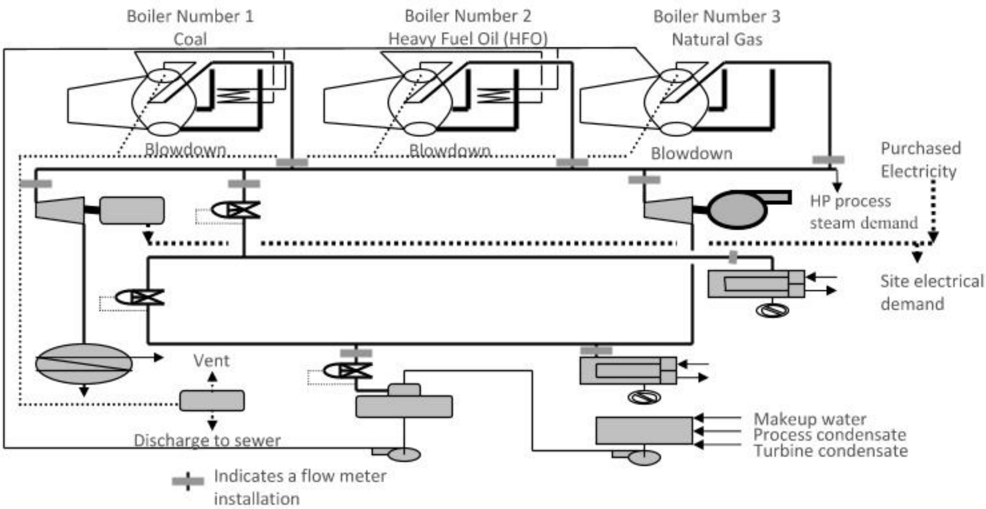


Fouling Issues

- Water-side fouling (scale) is typically managed through water treatment efforts
  - Significant events are corrected through chemical cleaning and hydro-blasting
- Fire-side fouling is managed through sootblowing and periodic off-line cleaning
  - Sootblowing is critical for solid fuel and heavy fuel oil combustion

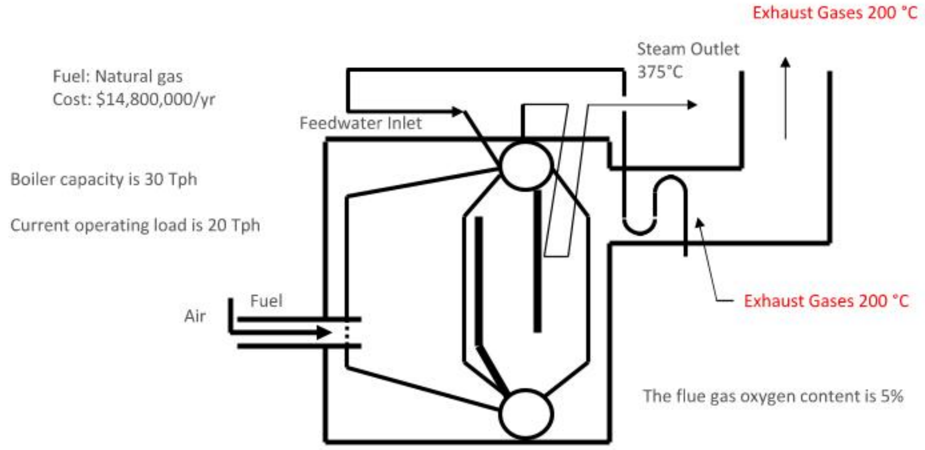
Common Stack Loss Reduction Opportunities

- Remove fireside fouling
  - Sootblowing
  - Offline cleaning
- Remove water side fouling
  - Prevention
  - High-pressure jet wash
  - Chemical cleaning
- Repair failed internal components
- Install heat recovery equipment

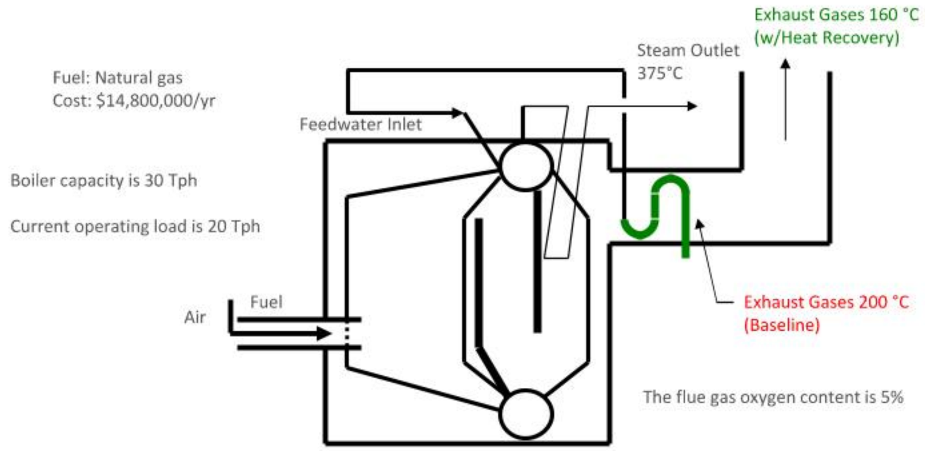


Steam System

Stack Loss Reduction Example



Stack Loss Reduction Example



Savings Analysis

$$\sigma_{savings} = \left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right)\dot{E}_{steam} = \left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right)\left[\dot{m}_{steam}\left(h_s - h_{fw}\right)\right]$$

Where

- η_1 and η_2 represent the current and the new boiler operating efficiencies
- E_{steam} represents the energy transferred in the boiler to make steam

Savings Analysis

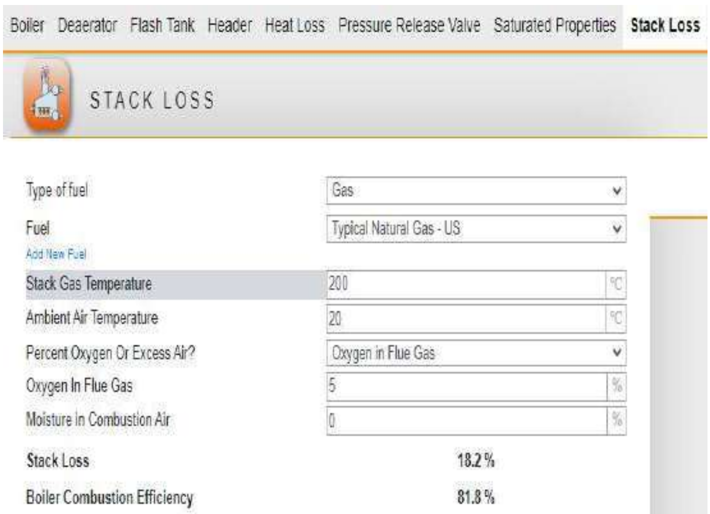
$$\sigma_{savings} = \left(1 - \frac{\eta_1}{\eta_2}\right)\frac{\dot{E}_{steam}}{\eta_1} = \left(1 - \frac{\eta_1}{\eta_2}\right)\dot{E}_{fuel\,1}$$

$$\sigma_{savings} = \left(1 - \frac{\eta_1}{\eta_2}\right)\dot{K}_{fuel\,1}$$

Where

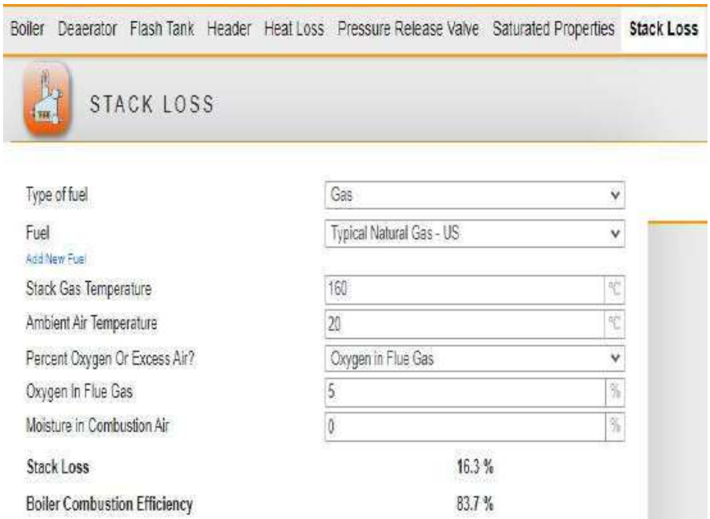
- $E_{fuel\ 1}$ represents the current fuel input energy to the boiler
- $K_{fuel\ 1}$ represents the cost of the current fuel input energy to the boiler

Stack Loss Calculator – Natural gas in MEASUR



- Stack loss table is developed for negligible combustibles and no condensation

Stack Loss Calculator – Natural gas in MEASUR



- Stack loss table is developed for negligible combustibles and no condensation

Savings Analysis

$$\sigma_{savings} = \left(1 - \frac{\eta_{existing}}{\eta_{adjusted}}\right) \dot{K}_{boiler}$$

$$\sigma_{savings} = \left[1 - \frac{81.8}{83.7}\right] \times 14{,}800{,}00 = \ \sim\$336{,}000$$

- MEASUR analysis indicates the same savings opportunity
- Corrosion and boiler loading must be considered
- Based on this analysis installation of a feedwater economizer will most probably result in less than a 1.0 year simple payback

MEASUR Assessment – Boiler Efficiency Improvement

- Caution when reporting savings from this assessment

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	Baseline	Feedwater Economizer
Percent Savings (%)	— —	2.0%
Fuel Usage (GJ/yr)	583,365.6	570,123.1
Fuel Cost ($/yr)	$14,584,140	$14,253,079
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m³/yr)	87,474.6	87,474.6
Water Cost ($/yr)	57,733	57,733
Power Generated (kW)	0	0
Process Use (GJ/yr)	39.4	39.4
Stack Loss (GJ/yr)	12.1	10.6
Vent Losses (GJ/yr)	0	0
Unrecycled Condensate Losses (GJ/yr)	8.7	8.7
Turbine Losses (GJ/yr)	0	0
Other Losses (GJ/yr)	7.2	7.2
Annual Emissions (tonne CO_2)	**29,337.46**	**28,671.49**
Annual Emissions Savings (tonne CO_2)	**—**	**665.96**
Annual Cost ($)	**19,021,874**	**18,690,812**
Annual Savings ($)	**—**	**331,062**

MEASUR Assessment – Boiler Efficiency Improvement

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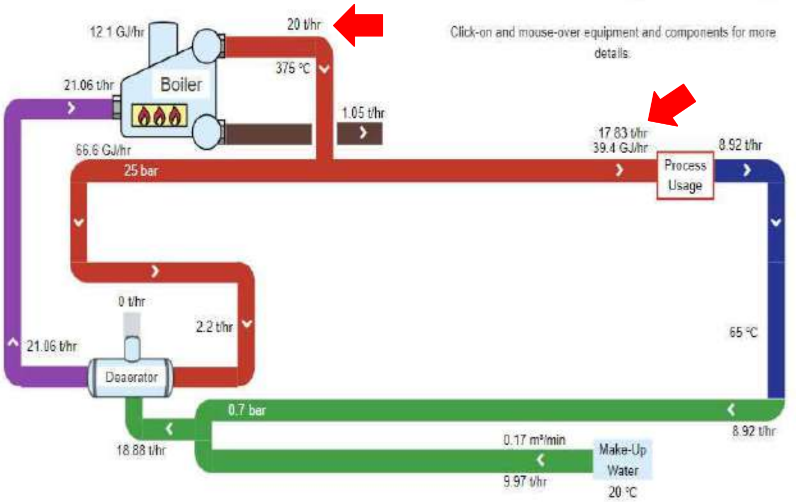

MEASUR Assessment – Boiler Efficiency Improvement

Key Points / Action Items

1. Monitor and record flue gas temperature with respect to:
   - Boiler load
   - Ambient temperature
   - Flue gas oxygen content
2. Compare flue gas temperature to previous, similar operating conditions
3. Maintain appropriate fire-side cleaning
4. Maintain appropriate water chemistry
5. Evaluate heat recovery component savings potential

Combustion Control Opportunity

- Improving combustion control often presents an energy management opportunity
- Controlling excess air (flue gas oxygen) to optimized levels increases boiler efficiency
- Several factors need to be considered to optimize excess air but the main factors are:
  - Fuel
  - Control mechanism
  - Emission regulations

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Combustion Analysis

- In a perfect world air and fuel would mix thoroughly and complete combustion would occur Fuel
  - Each molecule of fuel would find exactly react with the correct amount of oxygen for the combustion reaction to continue to completion

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Energy Release}$$

- In actual combustion processes, fuel and oxygen do not react perfectly

$$CH_4 + 2O_2 \underset{\text{Energy Release}}{\rightleftarrows} \alpha CO_2 + \beta H_2O + \gamma CO + \delta H_2 + \varepsilon CH_4 + \zeta O_2$$

- Un-reacted CH_4, CO and H_2 are *fuels* resulting from incomplete combustion

Source: US DOE Steam BestPractices Program

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Combustion Management – Principle 1

- Un-reacted CH_4, CO and H_2 degrade combustion operations
  - Safety problems
  - Health issues
  - Efficiency detriments

$$CH_4 + 2O_2 \underset{\text{Energy Release}}{\rightleftarrows} \alpha CO_2 + \beta H_2O + \gamma CO + \delta H_2 + \varepsilon CH_4 + \zeta O_2$$

- Combustion management strives to eliminate un-reacted fuel by adding extra oxygen to the combustion zone
  - Excess O_2 provided to the combustion zone **essentially eliminates un-reacted fuel**

Source: US DOE Steam BestPractices Program

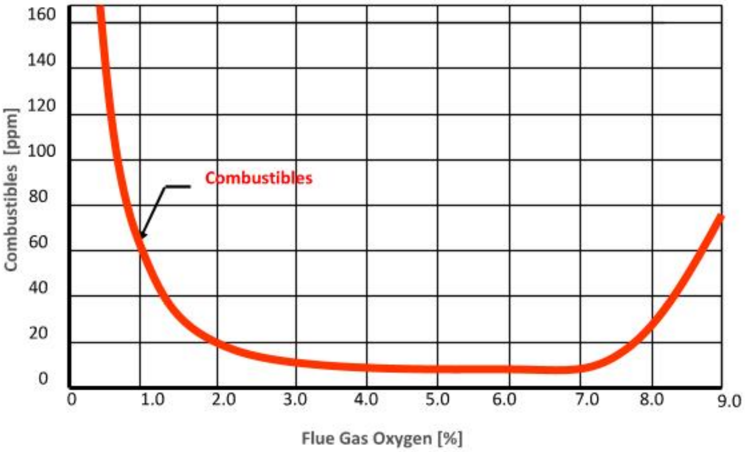
Combustion Management – Principle 2

- The extra oxygen added to ensure complete reaction of the fuel is heated by fuel from ambient temperature to the temperature of the exhaust gas

$$CH_4 + \underbrace{2O_2}_{+2(3.76)N_2} \underset{\text{Energy Release}}{\rightarrow} \alpha CO_2 + \beta H_2O + \gamma CO + \delta H_2 + \varepsilon CH_4 + \underbrace{\zeta O_2}_{+2(3.76)N_2}$$

- For most combustion processes *air* is used as the source of oxygen
  - A large amount of N_2 is heated from ambient temperature to exhaust gas temperature by fuel energy

Source: US DOE Steam BestPractices Program



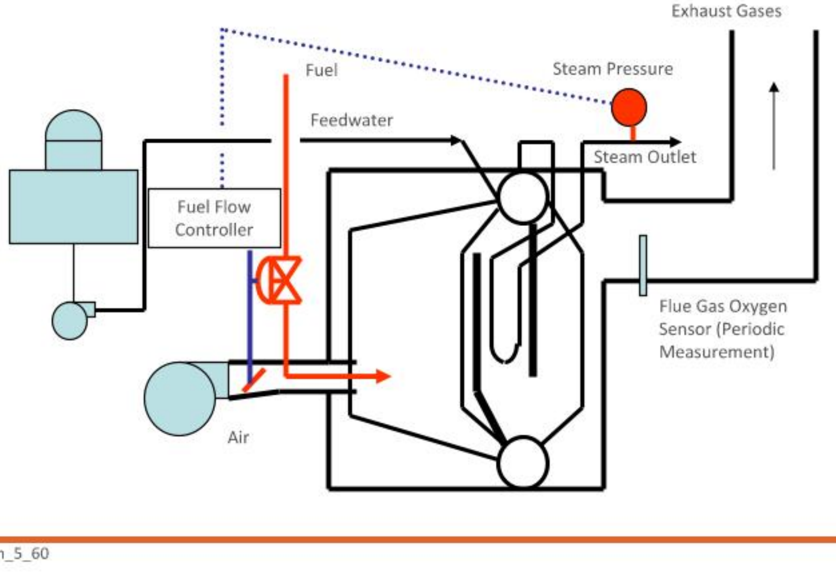
Minimum Oxygen Evaluation

- Minimum oxygen limits are determined by measuring combustibles

Source: US DOE Steam BestPractices Program

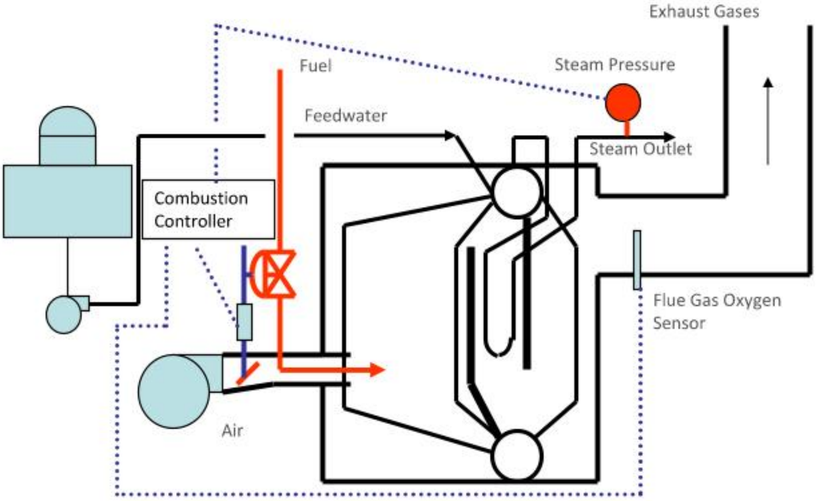
Combustion Management Strategy

- It is clear that excess air (amount of Oxygen) for the combustion process has to be controlled
- There are two main control strategies
  - Positional control
  - Automatic trim control
- Control of combustion air is done by
  - Dampers
  - Variable Frequency Drives
- Excess air is also a function of Boiler load
- Combustion zone (fire-box) pressure also needs to be controlled



Positioning Control

Source: US DOE Steam BestPractices Program



Automatic O_2 Trim Control

Source: US DOE Steam BestPractices Program

Typical Flue Gas Oxygen Content Control Parameters

Typical Flue Gas Oxygen Content Control Parameters								
Fuel	Automatic Control Flue Gas O_2 Content		Positioning Control Flue Gas O_2 Content		Automatic Control Excess Air		Positioning Control Excess Air	
	Min. [%]	Max. [%]	Min. [%]	Max. [%]	Min. [%]	Max. [%]	Min. [%]	Max. [%]
Natural Gas	1.5	3.0	3.0	7.0	9	18	18	55
Numb. 2 Fuel Oil	2.0	3.0	3.0	7.0	11	18	18	55
Numb. 6 Fuel Oil	2.5	3.5	3.5	8.0	14	21	21	65
Pulverized Coal	2.5	4.0	4.0	7.0	14	25	25	50
Stoker Coal	3.5	5.0	5.0	8.0	20	32	32	65

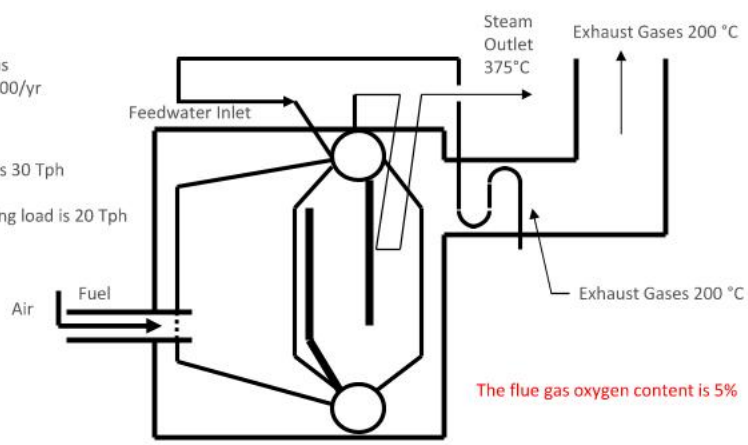
Source: US DOE Steam BestPractices Program

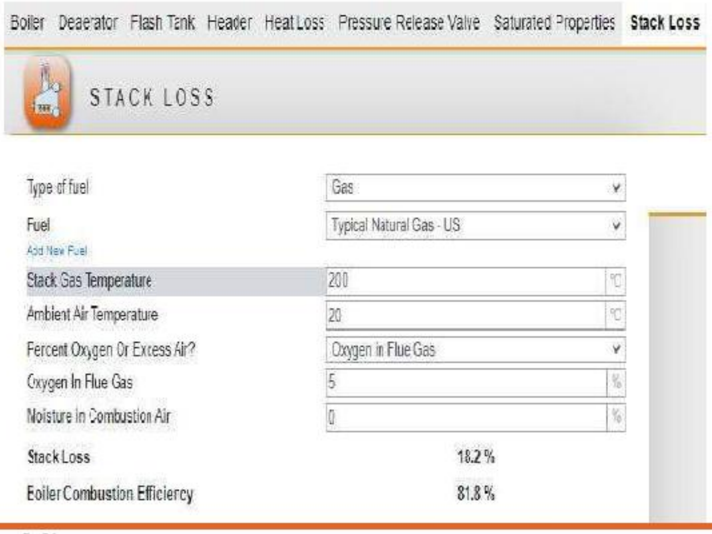
Stack Loss Reduction (Positional Controller) Example

Fuel: Natural gas
Cost: $14,800,000/yr

Boiler capacity is 30 Tph

Current operating load is 20 Tph





Stack Loss Calculator – Natural gas in MEASUR

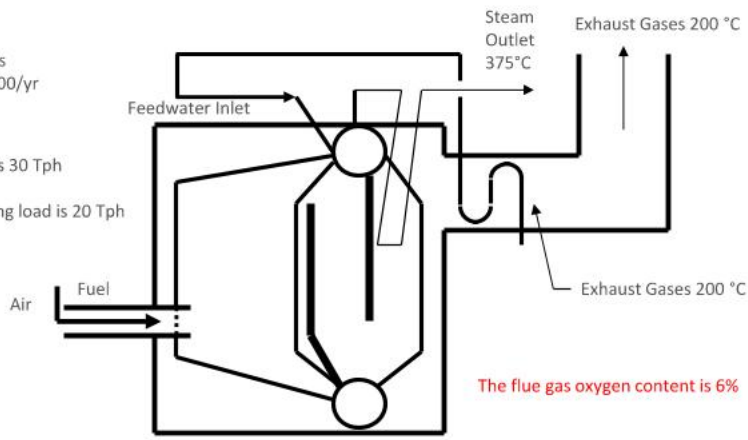
- Stack loss table is developed for negligible combustibles and no condensation

Stack Loss Reduction (Positional Controller) Example

Fuel: Natural gas
Cost: $14,800,000/yr

Boiler capacity is 30 Tph

Current operating load is 20 Tph



Stack Loss Calculator – Natural gas in MEASUR

- Stack loss table is developed for negligible combustibles and no condensation

Positional Controller Re-Tuning

- Energy Cost savings = Base Case Operating Cost – New Operating Cost

$$\sigma_{savings} = \left(1 - \frac{\eta_{existing}}{\eta_{adjusted}}\right)\dot{K}_{boiler}$$

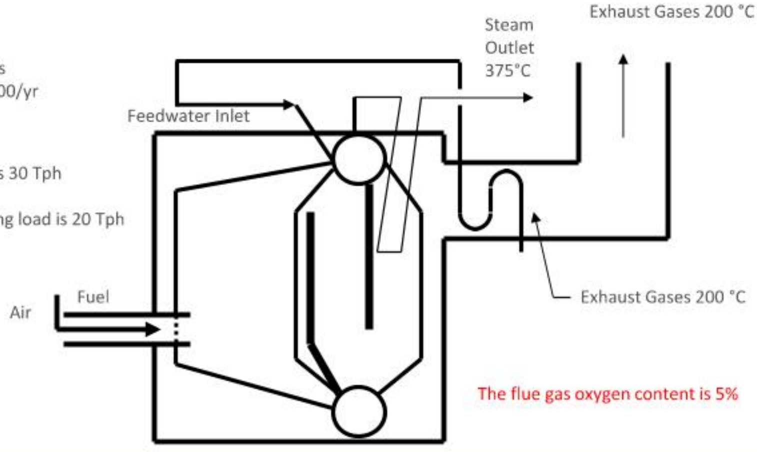
$$\sigma_{savings} = \left[1 - \frac{81.8}{81.4}\right] \times 14{,}800{,}00 = \sim -\$72{,}725$$

Stack Loss Reduction (Automatic O_2 Trim Controller) Example

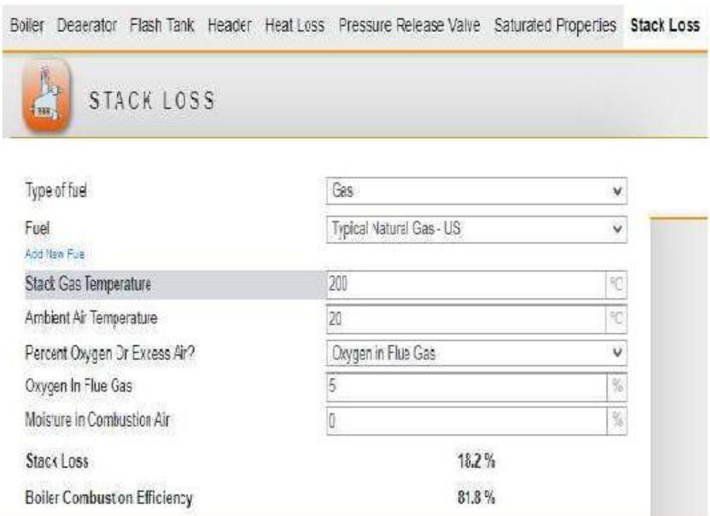
Fuel: Natural gas
Cost: $14,800,000/yr

Boiler capacity is 30 Tph

Current operating load is 20 Tph



The flue gas oxygen content is 5%



Stack Loss – Natural gas (Natural gas in MEASUR)

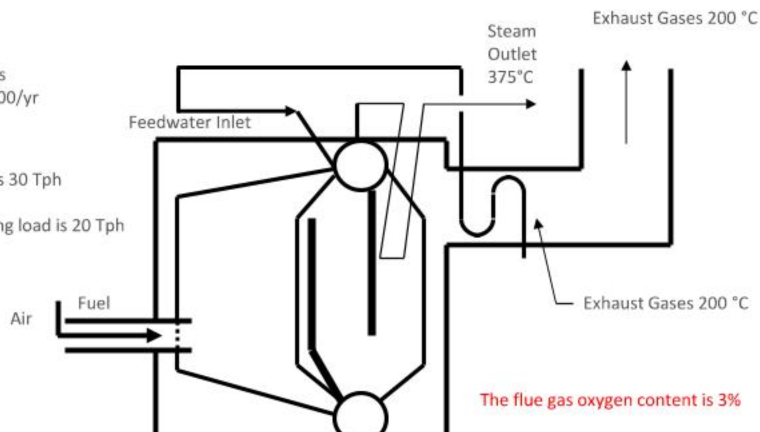
- Stack loss table is developed for negligible combustibles and no condensation

Stack Loss Reduction (Automatic O_2 Trim Controller) Example

Fuel: Natural gas
Cost: $14,800,000/yr

Boiler capacity is 30 Tph

Current operating load is 20 Tph



The flue gas oxygen content is 3%

STACK LOSS

Type of fuel	Gas
Fuel	Typical Natural Gas - US
Add New Fuel	
Stack Gas Temperature	200 °C
Ambient Air Temperature	20 °C
Percent Oxygen Or Excess Air?	Oxygen in Flue Gas
Oxygen In Flue Gas	3 %
Moisture in Combustion Air	0 %
Stack Loss	17.4 %
Boiler Combustion Efficiency	82.6 %

Stack Loss – Natural gas (Natural gas in MEASUR)

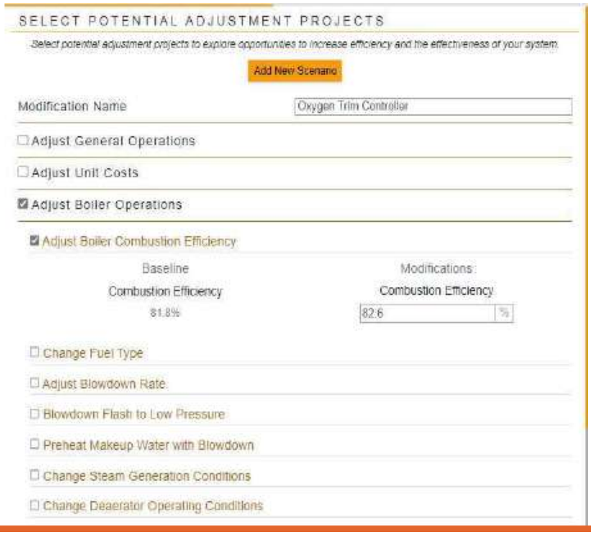
- Stack loss table is developed for negligible combustibles and no condensation

Install Automatic Oxygen Trim Controller

- Energy Cost savings = Base Case Operating Cost – New Operating Cost

$$\sigma_{savings} = \left(1 - \frac{\eta_{existing}}{\eta_{adjusted}}\right) \dot{K}_{boiler}$$

$$\sigma_{savings} = \left[1 - \frac{81.8}{82.6}\right] \times 14{,}800{,}00 = \sim\$143{,}350$$



MEASUR Assessment – Boiler Efficiency Improvement

RESULTS | SANKEY | HELP

	Baseline	Oxygen Trim Controller
Percent Savings (%)	— —	1.0%
Fuel Usage (GJ/yr)	583,365.6	577,715.6
Fuel Cost ($/yr)	$14,584,140	$14,442,890
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m³/yr)	87,474.6	87,474.6
Water Cost ($/yr)	57,733	57,733
Power Generated (kW)	0	0
Process Use (GJ/yr)	39.4	39.4
Stack Loss (GJ/yr)	12.1	11.5
Vent Losses (GJ/yr)	0	0
Unrecycled Condensate Losses (GJ/yr)	8.7	8.7
Turbine Losses (GJ/yr)	0	0
Other Losses (GJ/yr)	7.2	7.2
Annual Emissions (tonne CO_2)	**29,337.46**	**29,053.32**
Annual Emissions Savings (tonne CO_2)	**—**	**284.14**
Annual Cost ($)	**19,021,874**	**18,880,623**
Annual Savings ($)	**—**	**141,251**

MEASUR Assessment – Boiler Efficiency Improvement

Key Points / Action Items

1. Combustion management principles:
   - Add enough oxygen to react all of the fuel
   - Minimize the amount of extra air
   - Monitor combustibles to identify problems
2. Measure the oxygen content of boiler exhaust gas
3. Control oxygen content within a minimum and maximum range
   - Continuous - automatic O_2 trim control
   - Positioning control
4. Challenge the control range
   - Control upgrade
   - Combustion tuning

Fuel Switching & Boiler Operation Optimization

Fuel Switching

- Fuel selection can provide significant reductions in operating costs due to differences in energy costs and boiler efficiencies
  - Sometimes energy costs and maintenance expenditures are offsetting
  - Environmental issues are a significant concern associated with fuel selection
  - Fuel efficiency will generally be an influencing factor when changing fuel
- Each application will need an independent evaluation – there are NO thumb rules!

Boiler Operation Optimization

- Typically, very common scenario in multiple boiler configurations in industry
- Boiler operational optimization can take several forms
  - Shutdown a boiler
  - Reduce operations of the most expensive boiler while shifting load to other cost effective boilers
  - Dual fuel-firing and fuel hedging strategies may need to be considered
  - System reliability will need to be considered
  - Both steady state as well as dynamic load profile will need to be evaluated
- Each application will need an independent evaluation – there are NO thumb rules!

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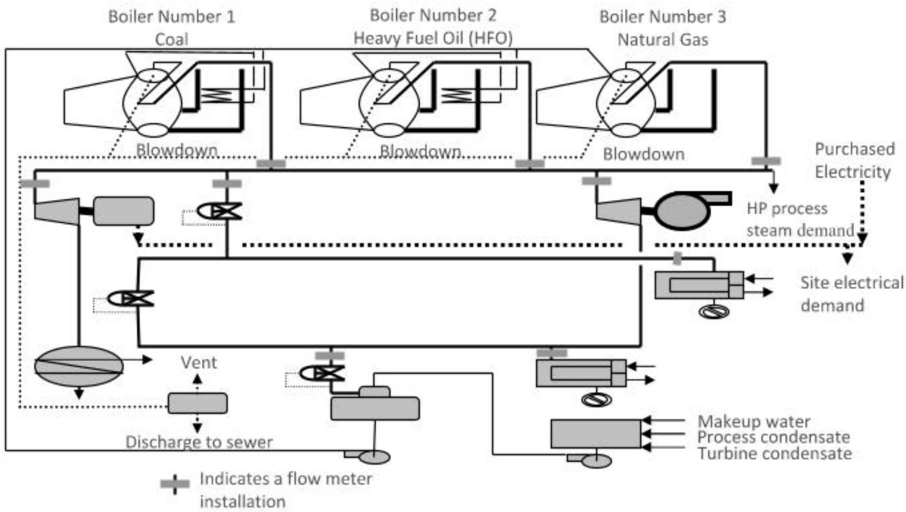

Steam System

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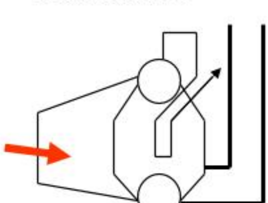
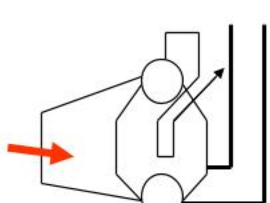
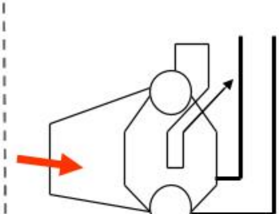
Steam conditions:
25 bars and 375°C



Fuel: Coal
Fuel cost: $5.4/GJ
Boiler capacity: 90 Tph
Steam production: **65 Tph**
Boiler efficiency: 85%



Fuel: Heavy Fuel Oil
Fuel cost: $18/GJ
Boiler capacity: 90 Tph
Steam production: **65 Tph**
Boiler efficiency: 84%



Fuel: Natural gas
Fuel cost: $25/GJ
Boiler capacity: 30 Tph
Steam production: **20 Tph**
Boiler efficiency: 80%

Fuel Switching & Steam Generation Optimization

- Quantify the economic benefit of increasing steam production by 1 Tph in the HFO boiler
- Quantify the economic benefit of increasing steam production by 1 Tph in the Coal boiler

Fuel Switching Calculation (1 Tph with HFO Boiler)

$$Savings\ from\ fuel\ switching = \sigma = Initial\ operating\ cost - Final\ operating\ cost$$

$$\sigma = \left(\dot{K}_1 - \dot{K}_2\right)\tau = \left(\frac{\dot{E}_{steam}}{\eta_1}\kappa_{fuel1} - \frac{\dot{E}_{steam}}{\eta_2}\kappa_{fuel2}\right)\tau = \dot{E}_{steam}\left(\frac{\kappa_{fuel1}}{\eta_1} - \frac{\kappa_{fuel2}}{\eta_2}\right)\tau$$

$$\sigma = \dot{m}_{steam}\left(h_{steam} - h_{fw}\right)\left(\frac{\kappa_{fuel1}}{\eta_1} - \frac{\kappa_{fuel2}}{\eta_2}\right)\tau$$

$$\sigma = 1{,}000\,\tfrac{kg}{hr}\left(3{,}181\,\tfrac{kJ}{kg} - 463.5\,\tfrac{kJ}{kg}\right)\left(\frac{25\,\frac{\$}{GJ}}{0.80} - \frac{18\,\frac{\$}{GJ}}{0.84}\right)8{,}760\,\tfrac{hrs}{yr}$$

$$\sigma = 234{,}000\,\tfrac{\$}{yr}$$

Fuel Switching Calculation (1 Tph with Coal Boiler)

$$Savings\ from\ fuel\ switching = \sigma = Initial\ operating\ cost - Final\ operating\ cost$$

$$\sigma = \left(\dot{K}_1 - \dot{K}_2\right)\tau = \left(\frac{\dot{E}_{steam}}{\eta_1}\kappa_{fuel1} - \frac{\dot{E}_{steam}}{\eta_2}\kappa_{fuel2}\right)\tau = \dot{E}_{steam}\left(\frac{\kappa_{fuel1}}{\eta_1} - \frac{\kappa_{fuel2}}{\eta_2}\right)\tau$$

$$\sigma = \dot{m}_{steam}\left(h_{steam} - h_{fw}\right)\left(\frac{\kappa_{fuel1}}{\eta_1} - \frac{\kappa_{fuel2}}{\eta_2}\right)\tau$$

$$\sigma = 1{,}000\,\tfrac{kg}{hr}\left(3{,}181\,\tfrac{kJ}{kg} - 463.5\,\tfrac{kJ}{kg}\right)\left(\frac{25\,\frac{\$}{GJ}}{0.80} - \frac{5.4\,\frac{\$}{GJ}}{0.85}\right)8{,}760\,\tfrac{hrs}{yr}$$

$$\sigma = 593{,}000\,\tfrac{\$}{yr}$$

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Fuel Switching Calculation (1 Tph with Coal Boiler)

$$Savings\ from\ fuel\ switching = \sigma = Initial\ operating\ cost - Final\ operating\ cost$$

$$\sigma = \left(\dot{K}_1 - \dot{K}_2\right)\tau = \left(\frac{\dot{E}_{steam}}{\eta_1}\kappa_{fuel1} - \frac{\dot{E}_{steam}}{\eta_2}\kappa_{fuel2}\right)\tau = \dot{E}_{steam}\left(\frac{\kappa_{fuel1}}{\eta_1} - \frac{\kappa_{fuel2}}{\eta_2}\right)\tau$$

$$\sigma = \dot{m}_{steam}\left(h_{steam} - h_{fw}\right)\left(\frac{\kappa_{fuel1}}{\eta_1} - \frac{\kappa_{fuel2}}{\eta_2}\right)\tau$$

$$\sigma = 1{,}000\,\tfrac{kg}{hr}\left(3{,}181\,\tfrac{kJ}{kg} - 463.5\,\tfrac{kJ}{kg}\right)\left(\frac{25\,\frac{\$}{GJ}}{0.80} - \frac{5.4\,\frac{\$}{GJ}}{0.85}\right)8{,}760\,\tfrac{hrs}{yr}$$

$$\sigma = 593{,}000\,\tfrac{\$}{yr}$$

NOTE: Analysis utilizes direct boiler efficiency (or complete indirect efficiency)

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MEASUR Assessment – Alternate Fuel

- Fuel switching is a common energy management activity
- MEASUR allows
  - The user to choose an alternate fuel from the standard fuel list
  - Input a fuel unit cost
- In general boiler efficiency will change as the fuel is changed
  - Fuel characteristics will impact stack loss
  - Boiler characteristics may change
    - Flue gas temperature may increase due to fouling
    - Flue gas oxygen content may change because of combustion characteristics
- Emissions will also change

Fuel Switching in MEASUR

- Economic impact can be calculated

	Baseline	Alternate Fuel
Percent Savings (%)	— —	61.0%
Fuel Usage (GJ/yr)	583,365.6	549,761.6
Fuel Cost ($/yr)	$14,584,140	$2,968,713
Annual Cost ($)	**19,021,874**	**7,406,446**
Annual Savings ($)	**—**	**11,615,428**

Fuel Switching – in MEASUR

- Economic impact of switching 20 tph steam from the Natural gas boiler to the coal-fired boiler
- Economic impact of switching 1 tph steam from the Natural gas boiler to the coal-fired boiler

$$\sigma_{savings} = \frac{11{,}615{,}428}{20} = \sim 580{,}000\ \frac{\$}{yr}$$

Factors Limiting Fuel Switching

- Environmental regulations
- Fuel storage and handling
- Boiler capabilities

Key Points / Action Items

1. Use a steam system model based on the laws of thermodynamics to quantify energy and cost savings opportunities
2. Fuel switching and boiler plant operations are excellent areas for optimization of steam systems – significant cost savings can be realized by applying optimal operating strategies
3. Each application will need an independent evaluation – there are NO thumb rules!

Common BestPractices - Generation

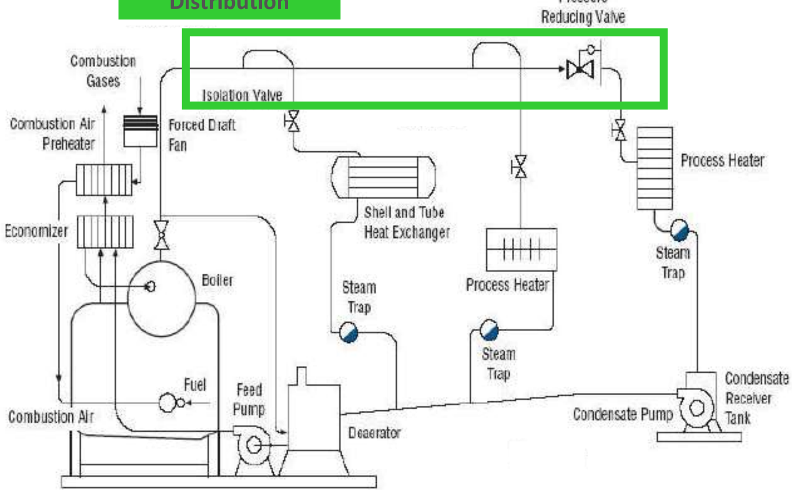
- Minimize excess air
- Install heat recovery equipment
- Clean boiler heat transfer surfaces
- Improve water treatment to reduce boiler blowdown
- Recover energy from boiler blowdown
- Add/restore boiler refractory
- Minimize the number of operating boilers
- Investigate fuel switching
- Optimize deaerator vent rate

Source: US DOE BestPractices Steam System Sourcebook

Section 6: Steam System Optimization – Distribution

- Steam Leaks
- Heat Transfer Loss Through Insulation

Distribution



Generic Steam System

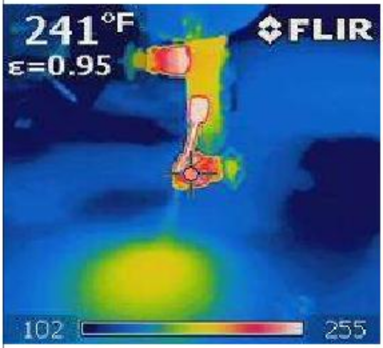
Source: US DOE Steam BestPractices Program

Steam Leaks

- End-user quote – "Steam leaks are an essential component of my system, if I don't hear or see them, I can't tell if my steam system is operating!"



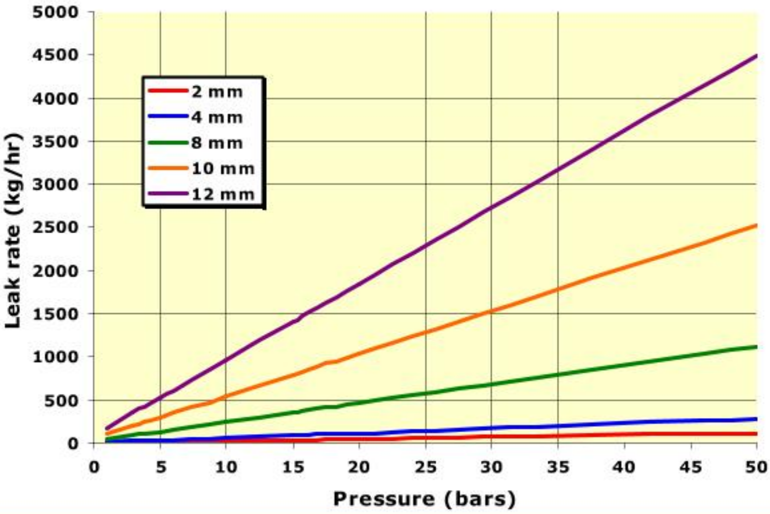
Steam Leaks



- Steam leaks occur everywhere but most common are places such as:
  - Flanges and gasketed joints
  - Pipe fittings
  - Valves - stems and packings
  - Steam traps
  - Relief valves
  - Pipe failures, etc.
- An "order of magnitude" steam loss estimate can provide enough information to determine if the repair must be made immediately, during a future shutdown, or online
- Pipe failures (steam leaks) often present a "safety issue" that demands immediate attention

Steam Leaks

- Methods to determine economic impact of steam leaks
  - Using MEASUR based model
  - Empirical and observation based – plume height
  - Measurement and calculation based via choked flow equation – Napier's equation
  - Field measurement with a pitot tube
  - Ultrasonic technique, specific manufacturers' instrument and protocol (standard) based
  - Other system or equipment balance methodologies
- Condensate leakage can be measured by stop watch and bucket methodology



Steam Leaks

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Steam Leaks

- Napier's choked flow equation

$$m_{steam} = 0.695 \times A_{orifice} \times P_{steam}$$

- This equation is valid for
  - Choked flow conditions: Exhaust pressure < $0.51 * P_{steam}$
  - Coefficient of discharge = 0.6
  - $A_{orifice}$ is area of orifice (or leakage) in mm^2
  - P_{steam} is the steam pressure in bars (absolute)

- Steam Leakage cost can be determined by multiplying the leakage rate with unit steam cost

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Example Steam System

- Steam leak of ~4 mm diameter orifice was found on the 2 bar header. Estimate the steam leak cost.

- Napier's choked flow equation

$$m_{steam} = 0.695 \times A_{orifice} \times P_{steam}$$

$$m_{steam} = 0.695 \times 12.56 \times 3 = 26.2\ kg / hr$$

- Unit Steam Cost: $93.72 per 1,000 kg

$$Leak\ Cost = m_{steam} \times \kappa_{steam}$$

$$Leak\ Cost = \frac{26.2 \times 93.72 \times 8{,}760}{1{,}000} \approx \$21{,}500/yr$$

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MEASUR Assessment for Steam Leaks

Modification Name	Steam Leak

☐ Adjust General Operations

☐ Adjust Unit Costs

☐ Adjust Boiler Operations

☐ Adjust Condensate Handling

☐ Adjust Heat Loss Percentages

☑ Adjust Steam Demand/Usage

☐ Adjust High Pressure Steam Usage

☐ Adjust Medium Pressure Steam Usage

☑ Adjust Low Pressure Steam Usage

Baseline	Modifications
Steam Usage	Steam Usage
70 t/hr	69.9738 t/hr

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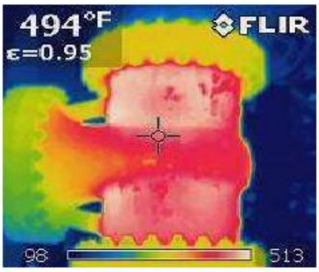
MEASUR Assessment for Steam Leaks

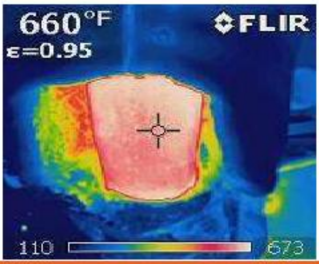
RESULTS SANKEY HELP

	Baseline	Steam Leak
Percent Savings (%)	——	
Fuel Usage (GJ/yr)	4,416,084	4,415,227.6
Fuel Cost ($/yr)	$110,402,099	$110,380,690
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m³/yr)	640,361.2	640,232.7
Water Cost ($/yr)	422,638	422,554
Power Generated (kW)	1,948.2	1,948.2
Process Use (GJ/yr)	320.7	320.6
Stack Loss (GJ/yr)	91.7	91.7
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	35.1
Annual Emissions (tonne CO_2)	**222,084.86**	**222,041.8**
Annual Emissions Savings (tonne CO_2)	**—**	**43.07**
Annual Cost ($)	**115,204,737**	**115,183,243**
Annual Savings ($)	**—**	**21,494**

Key Points / Action Items

1. Steam leaks occur in all plants and a continuous improvement type steam leak management program should be implemented in industrial plants
2. An “order of magnitude” steam loss estimate can provide enough information to determine if the repair must be made immediately, during a future shutdown, or online





Steam System Insulation

- Why is insulation necessary on steam systems?
  - Personnel safety – high temperatures
  - Minimize energy losses
  - Protection from ambient conditions
  - Preserve system integrity
- Typical areas of insulation improvement opportunities
  - Distribution headers
  - Inspection man-ways
  - Valves
  - Condensate return lines
  - End-use equipment
  - Storage tanks, vessels, etc.

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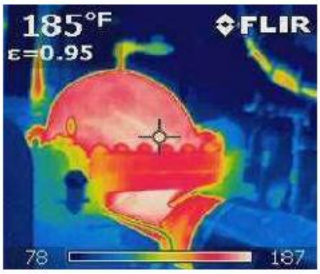

Steam System Insulation

- There are several reasons for damaged or missing insulation and hence, energy savings opportunities in the insulation area
  - Missing insulation due to maintenance activities
  - Missing / damaged insulation due to abuse
  - Damaged insulation due to accidents
  - Normal wear and tear of insulation due to ambient conditions
  - Valves and other components not insulated

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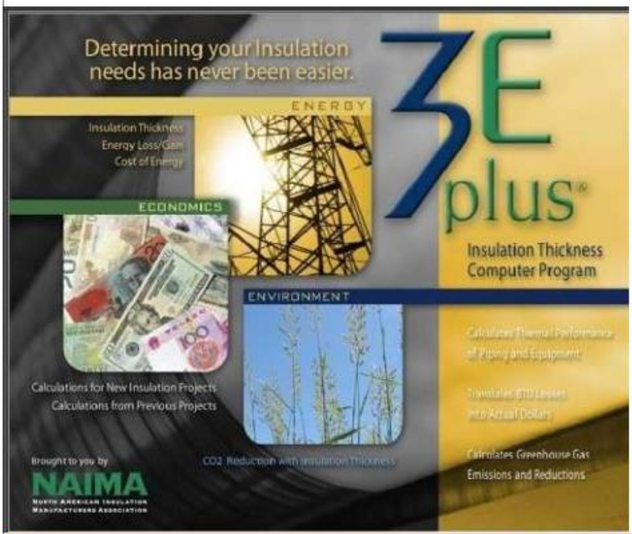
Steam System Insulation

- Some basic instruments, software and basic data required to quantify the economic impact of insulation
  - Infra-red thermography camera
  - Infra-red temperature gun
  - Measuring tape
  - 3E Plus insulation evaluation software
  - Operating information
    - Hours per year
  - Ambient conditions
    - Temperature
    - Wind

Insulation Tool – 3EPlus

- North American Insulation Manufacturers Association (NAIMA) developed 3EPlus - determines optimum insulation thickness for a wide variety of insulating materials
- Software outputs include:
  - Surface heat transfer loss
  - Insulation surface temperature
  - Simple payback of an insulating project



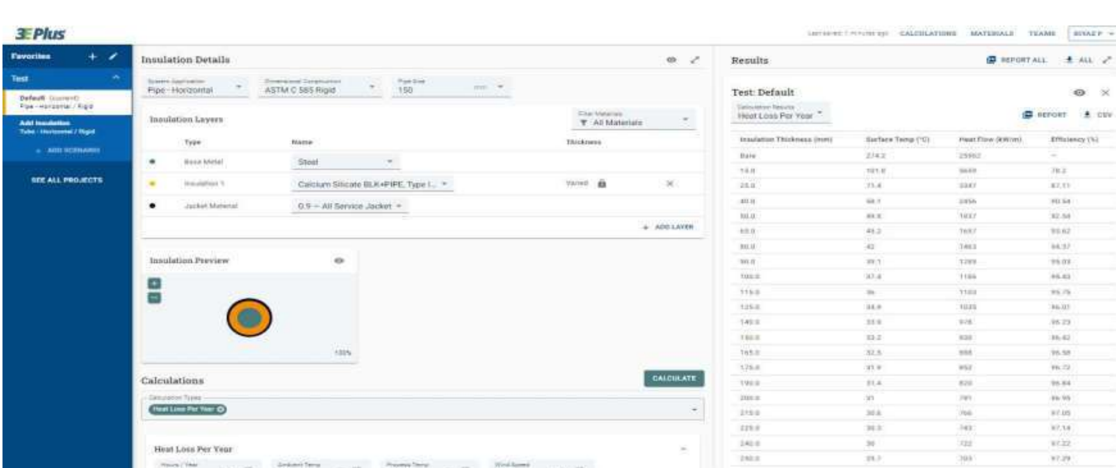
Insulation Evaluation Software

- Free Program available from NAIMA
- **E**nergy
  - Heat Loss
  - Cost Impact
- **E**nvironment
- **E**conomic Insulation Thickness
  - Life Cycle Cost Analysis

3EPlus Available ONLINE

https://www.3eplus.org

3EPlus ONLINE Version



https://www.3eplus.org

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Example Steam System - Missing Insulation

- A 10 m long section of 10 bar steam header is observed to be un-insulated
  - 25.4 cm nominal diameter
  - Steam temperature is ~362°C
- Estimate the economic insulation impact

Source: US DOE Steam BestPractices Program

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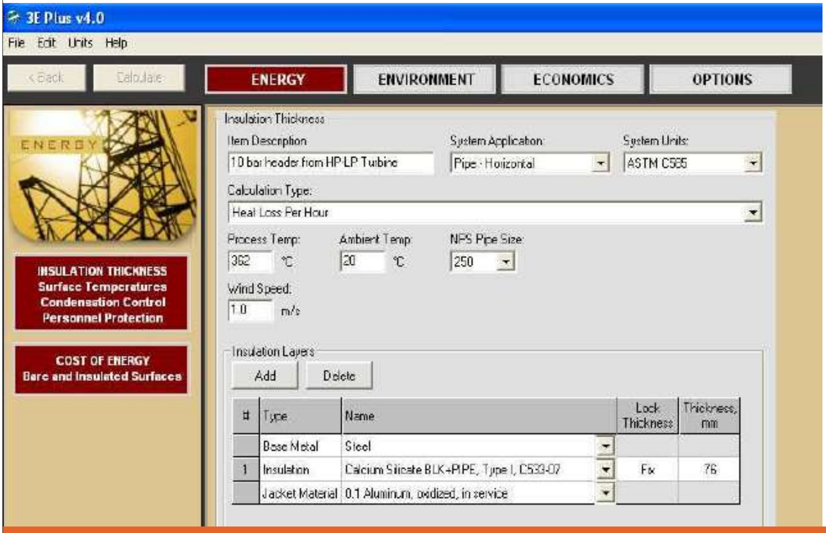

Insulation Evaluation

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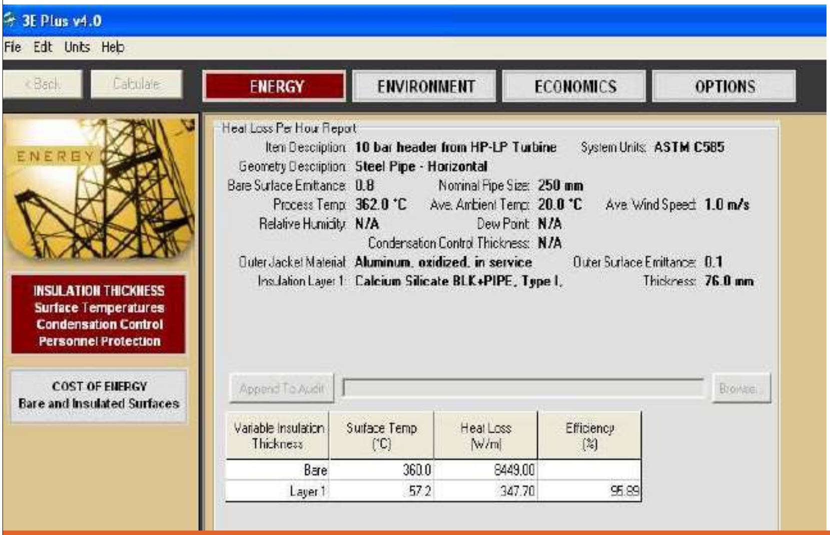

Insulation Evaluation

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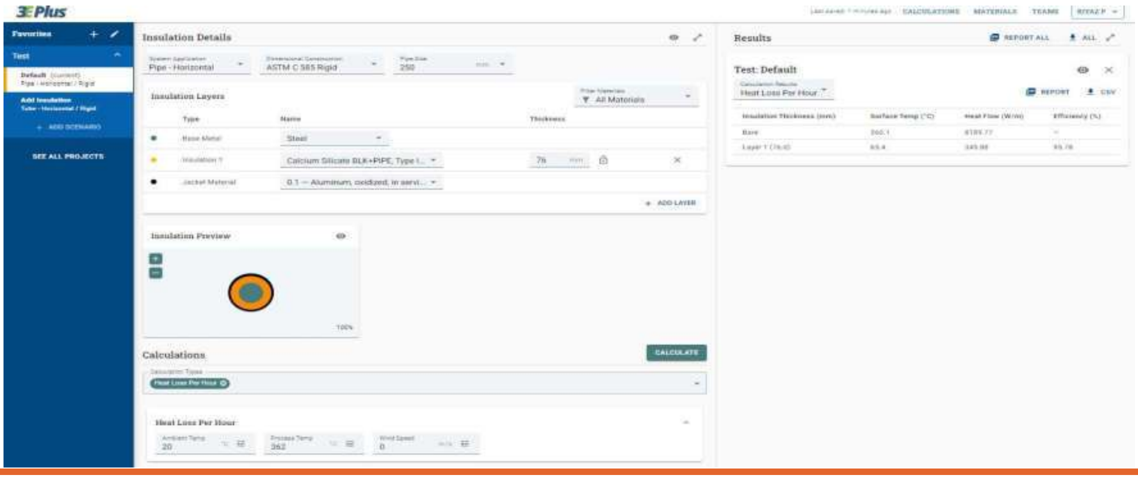
Insulation Evaluation (3EPlus Online)



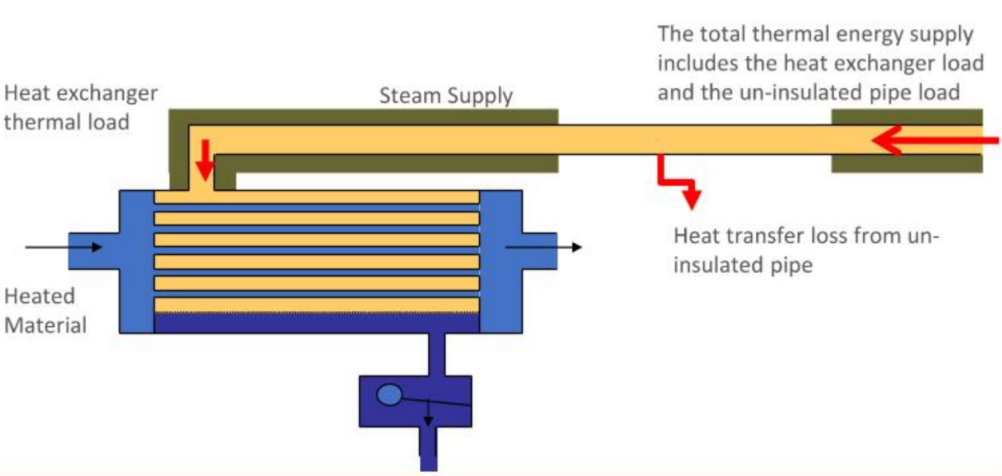
Insulation Evaluation

$$Q_{saved} = (8{,}190 - 346) \times 10 = 78.5\ kW$$

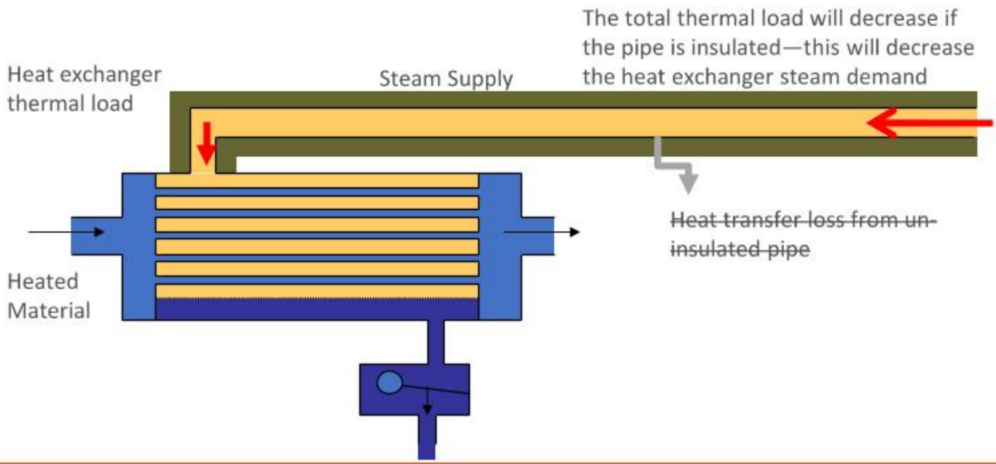
$$Fuelsaved = 78.5\ \frac{kJ}{s} \times 3{,}600\,\frac{s}{hr} \times 8{,}760\,\frac{hr}{yr} \times \frac{1}{0.80} = 3{,}094\,\frac{GJ}{yr}$$

$$Savings = 3{,}094\,\frac{GJ}{yr} \times 25.0\,\frac{\$}{GJ} = 77{,}350\,\frac{\$}{yr}$$

Equivalent Steam Demand



Equivalent Steam Demand



Energy Loss Converted to Steam Loss

MARGINAL STEAM COST	
High Pressure	$93.89 /t
Medium Pressure	$93.89 /t
Low Pressure	$93.72 /t

- If the energy impact is realized "at steam cost":

$$Q_{saved} = (8{,}190 - 346) \times 10 = 78.5\ kW$$

Location	Temperature [°C]	Specific Volume [m³/kg]	Enthalpy [kJ/kg]	Quality [%]	Pressure [bar(g)]
Steam	362	0.26130	3,181.0	****	10.00
Saturated vapor	184	0.17730	2,781.0	100.0	10.00
Saturated liquid	184	0.00113	781.5	0.0	10.00

Energy Loss Converted to Steam Loss

$$m_{steam} = \frac{Q_{saved}}{(h_{steam} - h_{condensate})}$$

$$m_{steam} = \frac{78.5}{(3{,}181 - 781.5)}$$

$$m_{steam} = 0.0327 \frac{kg}{s} = 117.8 \frac{kg}{hr}$$

Energy Loss Converted to Steam Loss

$$\sigma_{savings} = m_{steam} \times k_{steam}$$

If the cost of steam is known

$$\sigma_{savings} = 117.8 \times \frac{93.89}{1{,}000} = 11.06 \frac{\$}{hr}$$

$$\sigma_{savings} = 11.06 \times 8{,}760 = {\sim}97{,}000 \frac{\$}{yr}$$

- MEASUR steam demand reduction can also be utilized

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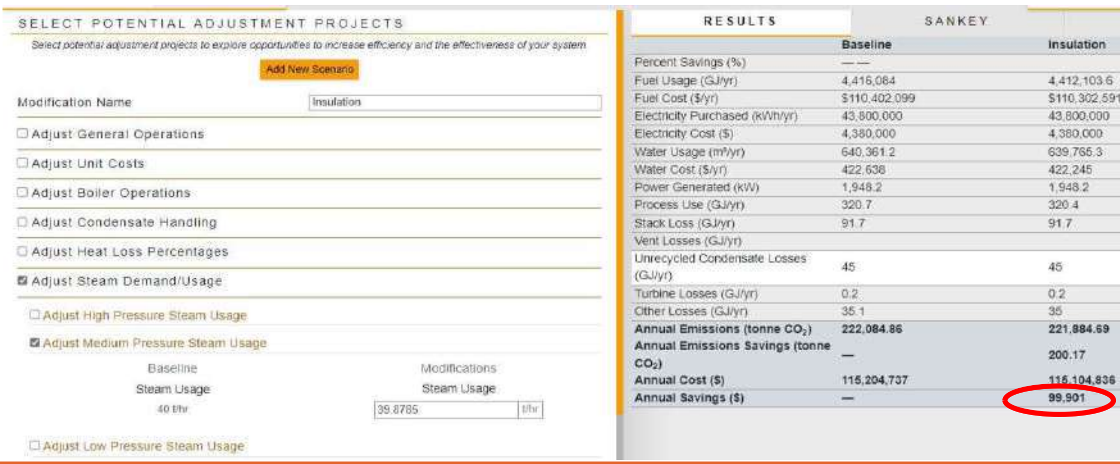
Insulation Evaluation using MEASUR



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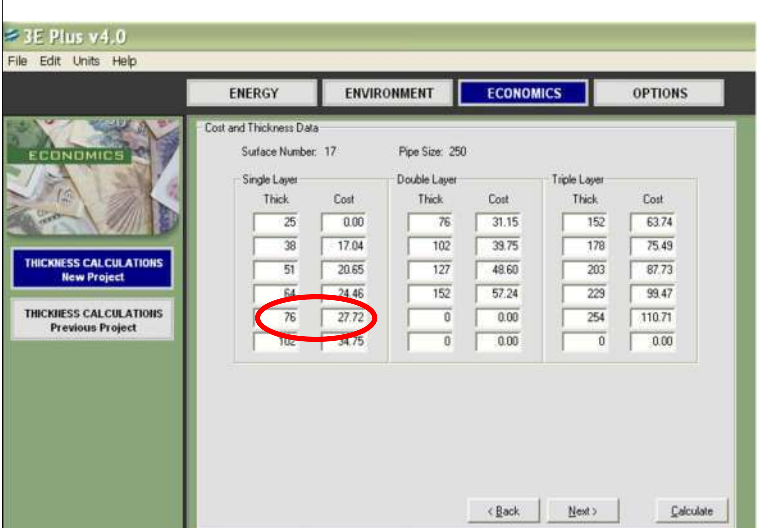

Insulation Evaluation

Insulation Evaluation

Common Insulation Issues

- Missing insulation due to maintenance activities
- Missing insulation due to abuse
- Damaged insulation
- Valves and other components not insulated

Insulation Evaluation for Non-Cogeneration Systems

- Steam systems providing thermal energy only (non-cogeneration) the cost of steam is essentially the cost of fuel divided by boiler efficiency
- 3E-Plus can be used directly to calculate insulation savings for non-cogeneration systems

Key Points / Action Items

1. There are several reasons for damaged or missing insulation
2. These areas result in significant energy losses and a continuous improvement type insulation appraisal (audit) program should be implemented in industrial plants
3. Some basic instruments, heat transfer models and process data are required to quantify the economic impact of missing or damaged insulation

Common BestPractices - Distribution

- Repair steam leaks
- Minimize vented steam
- Ensure that steam system piping, valves, fittings and vessels are well insulated
- Isolate steam from unused lines
- Minimize flows through pressure reducing stations
- Reduce pressure drop in headers
- Drain condensate from steam headers

Source: US DOE BestPractices Steam System Sourcebook

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Section 7: Steam System Optimization –Steam Demand (End Use)

- Steam Demand (End Use)
- MEASUR Steam Demand Savings Projects

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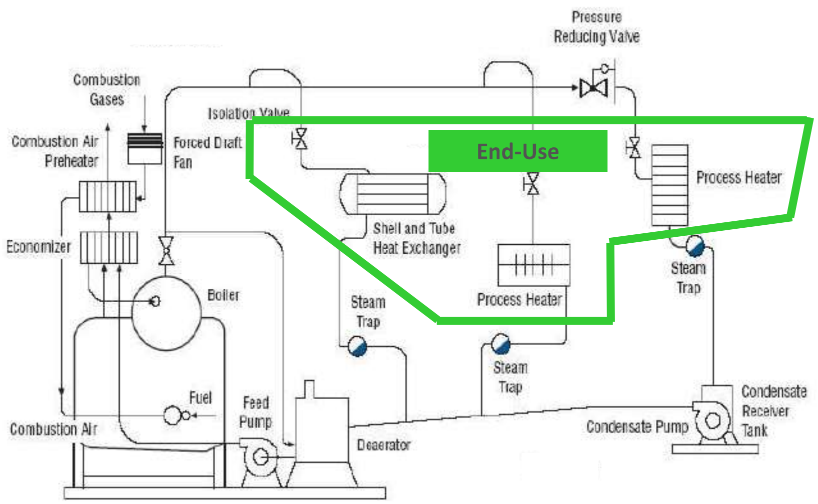


Generic Steam System

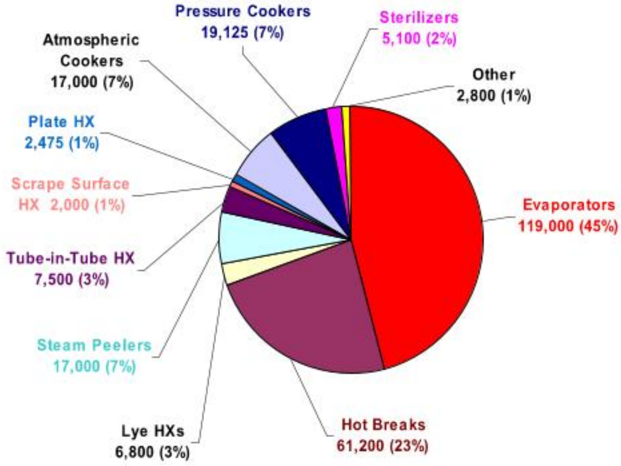
Source: US DOE Steam BestPractices Program

Steam Demand

- Steam demands take on many different forms
- Reducing steam consumption can often result in the most significant energy reduction opportunities
  - Eliminate inappropriate steam use
  - Reduce appropriate steam use
- Nevertheless, it is extremely difficult to cover end-uses that are specific to industrial processes in a general class
  - Hence, general methods will be described and tools provided to capture and quantify steam demand savings

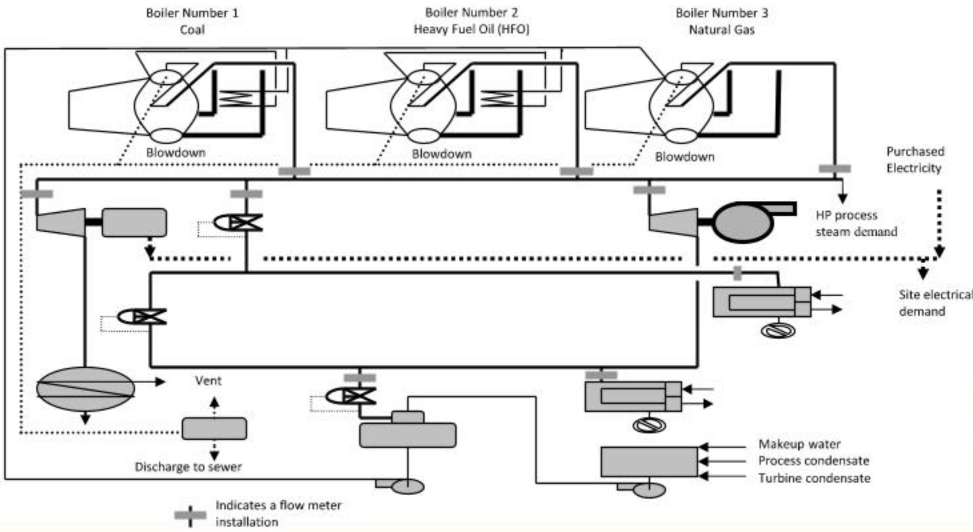
Some Common Steam End-Uses

- Distillation towers
- Dryers
- Evaporators
- Heat Exchangers
- Reboilers
- Reformers
- Steam ejectors / injectors
- Strippers
- Thermocompressors
- Absorption chillers
- Humidifiers
- Preheat / Reheat Air Handling Coils



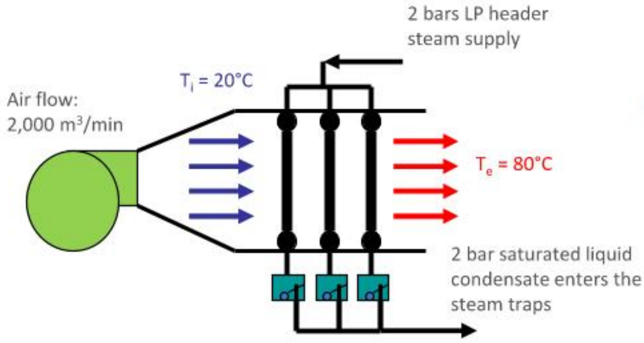
A Steam End-Use* Distribution Pie-Chart

* Food & Beverage – Vegetable & Fruit Juices



Steam System

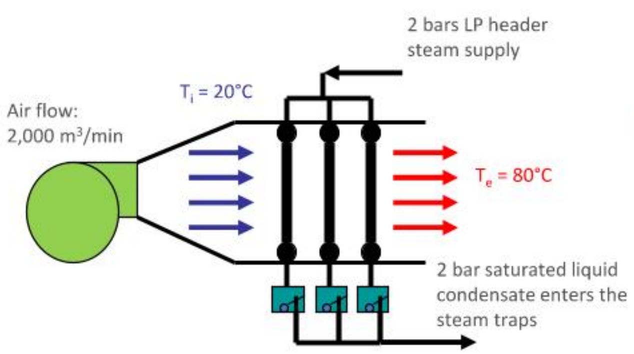
Example Steam Demand (Pre-heat air)



- A process requires air to be heated to 80°C
- Outside air is currently being supplied to the process oven

Source: US DOE Steam BestPractices Program

Example Steam Demand (Pre-heat air)

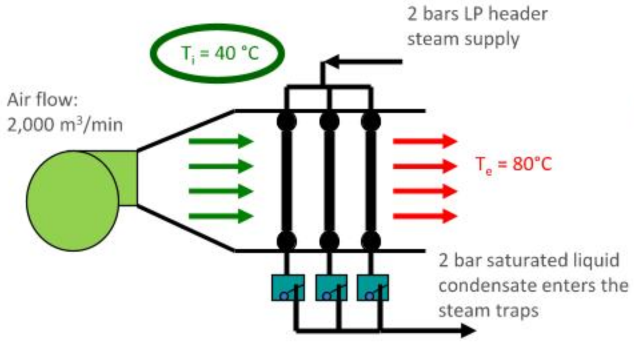


$$Q_{air} = m_{air} C_{p\_air} \left(T_{out} - T_{in}\right)_{air}$$

$$Q_{air} = 2{,}000 \times 1.188 \times 1.006 \times (80 - 20) \times \frac{1}{60}$$

$$Q_{air} = 2{,}391\, kW$$

Source: US DOE Steam BestPractices Program



Example Steam Demand (Pre-heat air)

$$Q_{air} = m_{air} C_{p\_air} (T_{out} - T_{in})_{air}$$

$$Q_{air} = 2{,}000 \times 1.188 \times 1.006 \times (80 - 40) \times \frac{1}{60}$$

$$Q_{air} = 1{,}594\ kW$$

Source: US DOE Steam BestPractices Program

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Example Steam Demand (Pre-heat air)

- Energy Savings = 2,391 – 1,594 ≈ 796 kW

$$m_{steamsaved} = \frac{EnergySavings}{(h_{steam} - h_{condensate})}$$

$$m_{steamsaved} = \frac{796}{(3{,}181 - 561.5)} \times 3{,}600$$

$$m_{steamsaved} = 1{,}094\ \frac{kg}{hr}$$

- Steam saved = 1.094 * 8,760 = 9,582 tonnes/yr
- Unit cost of steam generation: $93.72 per tonne
- Annual cost savings = $898,000
- This same analysis can be done using Steam Demand Savings in MEASUR

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MEASUR Assessment - Steam Demand Savings

Modification Name: Steam Demand

- ☐ Adjust General Operations
- ☐ Adjust Unit Costs
- ☐ Adjust Boiler Operations
- ☐ Adjust Condensate Handling
- ☐ Adjust Heat Loss Percentages
- ☑ Adjust Steam Demand/Usage
  - ☐ Adjust High Pressure Steam Usage
  - ☐ Adjust Medium Pressure Steam Usage
  - ☑ Adjust Low Pressure Steam Usage

Baseline	Modifications
Steam Usage	Steam Usage
70 t/hr	68.906 t/hr

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MEASUR Assessment - Steam Demand Savings

RESULTS | SANKEY | HELP

	Baseline	Steam Demand
Percent Savings (%)	— —	1.0%
Fuel Usage (GJ/yr)	4,416,084	4,380,326.3
Fuel Cost ($/yr)	$110,402,099	$109,508,157
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m^3/yr)	640,361.2	634,994.5
Water Cost ($/yr)	422,638	419,096
Power Generated (kW)	1,948.2	1,948.2
Process Use (GJ/yr)	320.7	317.8
Stack Loss (GJ/yr)	91.7	91
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	44.7
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	34.8
Annual Emissions (tonne CO_2)	**222,084.86**	**220,286.61**
Annual Emissions Savings (tonne CO_2)	**—**	**1,798.25**
Annual Cost ($)	**115,204,737**	**114,307,254**
Annual Savings ($)	**—**	**897,483**

Key Points / Action Items

1. There are several end-uses of steam in industrial plants
2. Do a steam end-use balance in an industrial plant and identify the largest steam end-users in a plant
3. Reduce steam end-use by
   - Improving the efficiency of the process
   - Shifting steam demand to a waste heat source or lower pressure steam available in the plant

Common BestPractices – End-Use

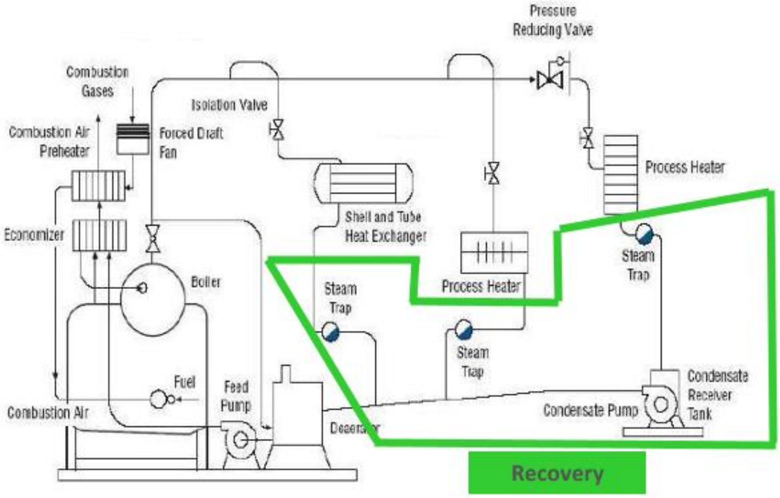
- Reduce steam usage by a process
  - Improving the efficiency of the process
  - Shifting steam demand to a waste heat source
- Reduce the steam pressure needed by process, especially in cogeneration systems
- Upgrade low pressure (or waste) steam to supply process demands
- Process integration leading to overall energy optimization of the plant

Source: US DOE BestPractices Steam System Sourcebook

Section 8: Steam System Optimization – Condensate Recovery

- Types of Steam Traps
- Steam Trap Management Program
- MEASUR Evaluations & Economic Impacts
- Evaluation of Condensate Recovery Systems
- Condensate Flash Tanks
- Condensate Tank Vents
- MEASUR Evaluations & Economic Impacts

Generic Steam System



Source: US DOE Steam BestPractices Program

Steam Traps

- Traps serve several vital operating functions for a steam system
  - During start-up, they allow air and large quantities of condensate to escape
  - During normal operation, they allow collected condensate to pass into the condensate return system, while minimizing (or eliminating) loss of steam
- There are different kinds of steam traps and hence, functionality and principles of operation must be understood
- All plants should have an effective steam trap management program
- Steam trap failures will result in energy loss in most cases, but they will surely result in system operation problems, safety and reliability issues in all cases

Types of Steam Traps

- Thermostatic Traps
  - Bellows*
  - Bimetallic*
- Mechanical Traps
  - Ball Float
  - Float and Lever
  - Inverted Bucket*
  - Open Bucket
  - Float and Thermostatic*
- Thermodynamic Traps
  - Disc*
- Orifice Traps
  - Orifice Plate
  - Venturi Tube

*** - Most commonly used**

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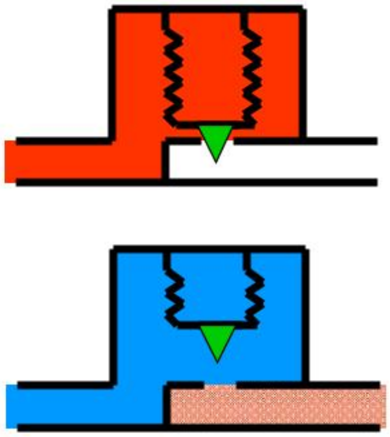

Thermostatic Steam Traps

- Responds to temperature changes
- A bellows or a bimetallic strip closes the valve with high temperature steam
- When condensate (typically, sub-cooled) collects – the bellows contracts and opens the valve to let condensate drain out

Source: US DOE Steam BestPractices Program

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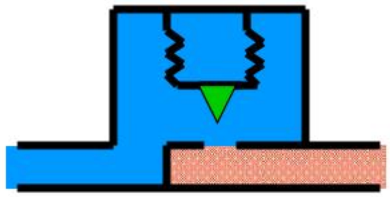

Thermostatic Steam Traps

- Opens to subcooled condensate
- Depending on subcooling can discharge condensate or condensate and flash steam
- Allows energy recovery from condensate
- Significant air removal capability

Source: US DOE Steam BestPractices Program

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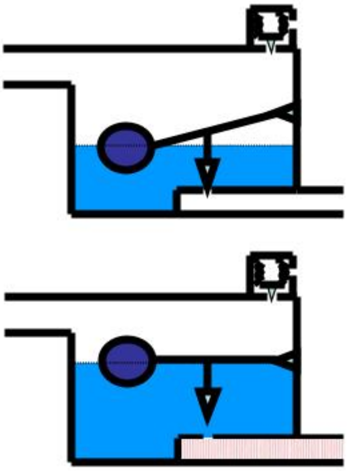

Float & Thermostatic Trap (F&T)

Mechanical Steam Traps

- Opens to saturated and/or sub-cooled condensate
- Will discharge condensate and flash steam
- Significant air removal and startup capabilities
- Modulating type operation

Source: US DOE Steam BestPractices Program

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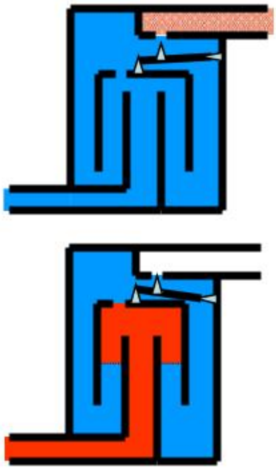


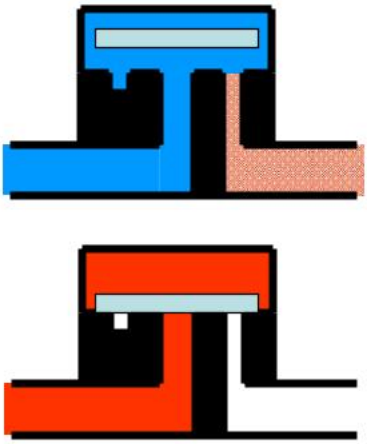
Inverted Bucket Trap (Open Float)

Mechanical Steam Traps

- Opens to saturated and/or sub-cooled condensate
- Will discharge condensate and flash steam
- Limited air removal and startup capabilities
- Application in superheated steam service should be questioned
- Intermittent operation

Source: US DOE Steam BestPractices Program

Thermodynamic Steam Traps



Disc Trap

- Works on the difference in kinetic energy (velocity) between condensate and steam to operate a valve
- Opens to saturated condensate
- Will discharge condensate and flash steam
- Intermittent operation
- Can be equipped with thermostatic element to improve air removal

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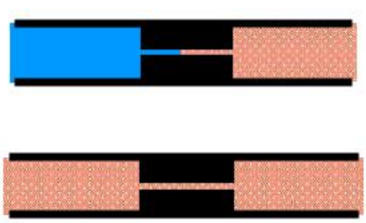
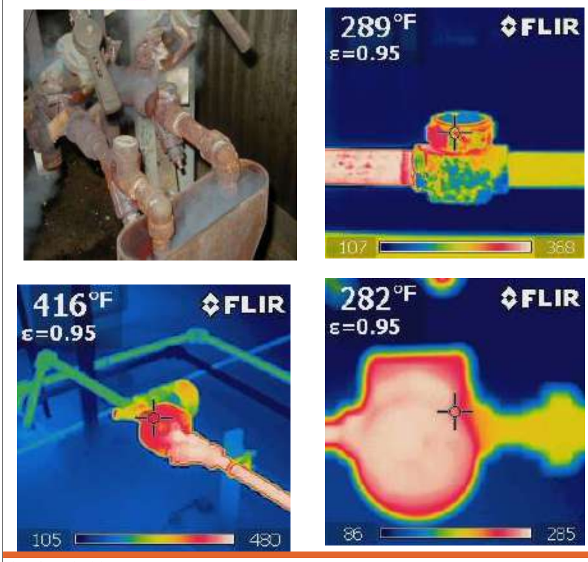
Orifice Steam Traps

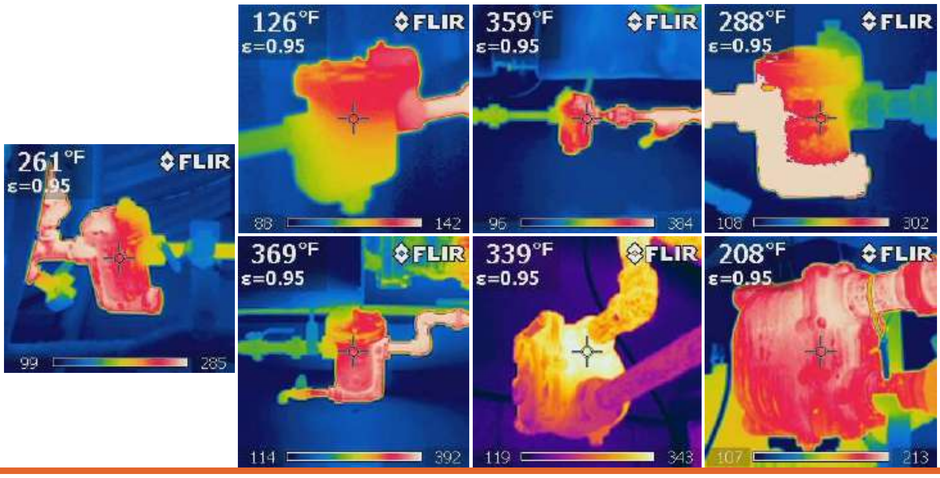


- No moving parts
- Continuous operation
- Common applications are steady loads
- Limited air removal capability due to orifice limitations
- Its designed for a specific amount of condensate removal
- If there is no condensate, then a small amount of steam leaks continuously



Steam Traps in the Field

Steam Traps in the Field



Steam Trap Failures

- There have been numerous studies in the industry and one of the more statistically accepted "rule of thumb" is that 10% of traps fail every year
- This depends on several factors and can be very industry specific also
- The main failure modes are:
  - Failed closed
  - Failed opened
  - Failed partially leaking or partially closed
- Failed open and failed closed result in the greatest system impacts
  - These failure modes are the most readily recognized
  - These failures should be of first priority

Steam Trap Investigation for Performance

- There are several methods for investigating steam trap performance
  - Visual
  - Acoustic
  - Thermal
- Most times, using only one method maybe inconclusive – so the following is recommended
  - Combination of methods
  - Additional process or system information, is required
- New state-of-the-art in-trap (real-time) monitoring is available for some steam traps

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Visual Steam Trap Investigation

- Limited in applicability
  - Most condensate systems are closed
  - Safety and practicality limit the use of this method
- Individual trap operation and application must be understood
  - Intermittent
  - Continuous
- Several traps can return condensate via a cascaded condensate return system – condensate receiver vent becomes the point of visual inspection

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Acoustic Steam Trap Investigation

- Many instruments are available
  - Screw driver
  - Stethoscope
  - Ultrasonic devices
- Individual trap operation and application must be understood
- Ultrasonic sensing is typically the most practical
- Some manufacturers have tools that can take the acoustic signature of steam flow through the trap and use that information to detect failure

Thermal Steam Trap Investigation

- Many instruments are available
  - Temperature stick
  - Infra-red temperature gun
  - Infra-red thermography camera
- Individual trap operation and application must be understood
- Data can be inconclusive
  - Condensate and steam will take a temperature drop while going through an orifice – hence, difficult to say if trap is failed open!

Real-time (SMART) Steam Trap Investigation

- Continuous testing of steam traps
- Uses combination of methods
  - Thermal
  - Acoustic
- Can be used on critical steam traps
- Allows for notifications on DCS, web-platforms, phones, etc.
- Available via several communication platforms

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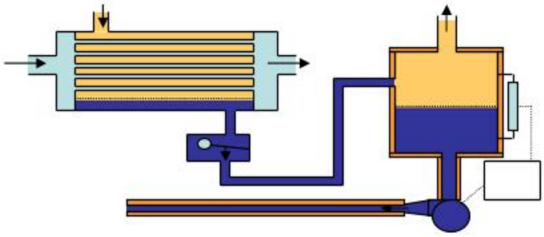
Steam Trap Survey - Condensate Recovery Investigation



- Is condensate being recovered?
- Is the condensate recovered *to the boilers* with the greatest practical thermal energy?
- Does the condensate recovery system place excessive backpressure on the traps?
- Is flash steam recovery applicable?
- Design the condensate recovery system for the greatest effectiveness

Source: US DOE Steam BestPractices Program

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Steam Trap Installation

- Each trap must be installed properly
- Non-condensable gas and startup considerations must be targeted
- The condensate collection system must be considered
  - Backpressure considerations
  - Lift considerations
  - Two-phase flow considerations

Effective Steam Trap Management Program

- Maintain a steam trap database
  - Type of trap, model number, size, etc
  - Application
  - Energy loss if failed open
  - Problems if failed closed
  - When was the last recorded failure, repair
- Prioritize repairs based on loss estimates and criticality of steam system and production operations
- Daily monitor receiver vents
- Inspect all traps at least once a year
- Trap maintenance training is essential

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Steam Trap Savings Analysis

MARGINAL STEAM COST

High Pressure	$93.89 /t
Medium Pressure	$93.89 /t
Low Pressure	$93.72 /t

- Conduct a Steam Trap Audit
  - Use orifice size and calculate steam leak flow
  - Use MEASUR Assessment and the demand savings on each header level
  - Marginal cost of steam accounted properly for cogeneration systems

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Steam Trap Savings Analysis

Location Number	Location Description	FLOOR LEVEL	Elevation	Manufact	Mod	Orif	Line Si.	Pressure	Servic	2019 New Comments	Trap Conditic	Estimated Steam Loss per year/100	Estimated Dollar Loss per year
139T	WEST OF SOUTH DRY BAY, OVERHEAD	5TH FLOOR	16'	ARMINT	30-B4		1-1/4"	30	DRIP		CP		$1,500.00
140T	WEST OF SOUTH DRY BAY, OVERHEAD	5TH FLOOR	12'	ARMINT	30-B6		1-1/2"	30	PROCESS		OK		
141T	NW OF SOUTH DRY BAY, OVERHEAD	5TH FLOOR	18'	ARMINT	1811		3/4"	30	DRIP		OK		
142T	NW OF SOUTH DRY BAY, OVERHEAD	5TH FLOOR	18'	ARMINT	30-A3		3/4"	30	PROCESS		VO		
143T	ABOVE VP-766, OVERHEAD	5TH FLOOR	11'	ARMINT	800		3/4"	30	HEATER	HEATER IS IN NORTH DRY BAY	VO		
144T	ABOVE VP-766, OVERHEAD	5TH FLOOR	9'	ARMINT	1811		3/4"	130	DRIP	STRAHMAN STATION IS IN NORTH DRY BAY	OK		
145T	WEST SIDE OF E-306	5TH FLOOR	1'	ARMINT	2010		3/4"	130	DRIP		VO		

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MEASUR Assessment - Steam Trap Analysis

- Work with open failed steam traps and prepare a list of traps failed at each pressure level

$$m_{steam} = 0.695 \times A_{orifice} \times P_{steam}$$

Key Points / Action Items

1. There are different kinds of steam traps and hence, functionality and principles of operation must be understood
2. Major steam trap failure modes - open / closed
3. An effective steam trap management program must be in place
4. There are several commercially available tools for steam trap investigations
5. Conduct a steam trap audit at least once a year and repair/replace defective traps
6. Steam trap manufacturers are a valuable resource

Condensate Recovery

- Condensate is produced after steam has transferred all its thermal energy and condensed into water
- Nevertheless, there is significant thermal energy in condensate
- Every unit of condensate returned implies one less unit of make-up required
- Returning condensate
  - Reduces energy (steam required) in deaerator
  - Reduces make-up water
  - Reduces chemicals for water treatment
  - Reduces quenching water
  - May reduce blowdown

Condensate Recovery

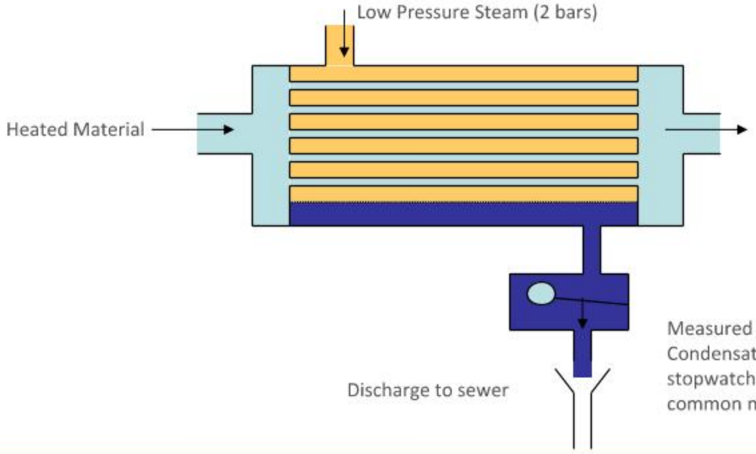
- Condensate typically has worth
  - Energy
  - Make-up water reduction
    - This generally improves feedwater quality
      - Resulting in a reduction in boiler blowdown
  - Chemical
- Condensate recovery costs generally center on the recovery system piping
  - Recovery equipment
  - Return piping

Condensate Recovery

- Condensate receivers serving “areas” can reduce project costs
- Condensate receivers and flash tanks serve to reduce the amount of steam entering the condensate return piping reducing flow restriction problems
- Contaminated condensate is a critical issue
- Receiver vents are indicative of trap failures
- Pump NPSH issues must be investigated

Source: US DOE Steam BestPractices Program

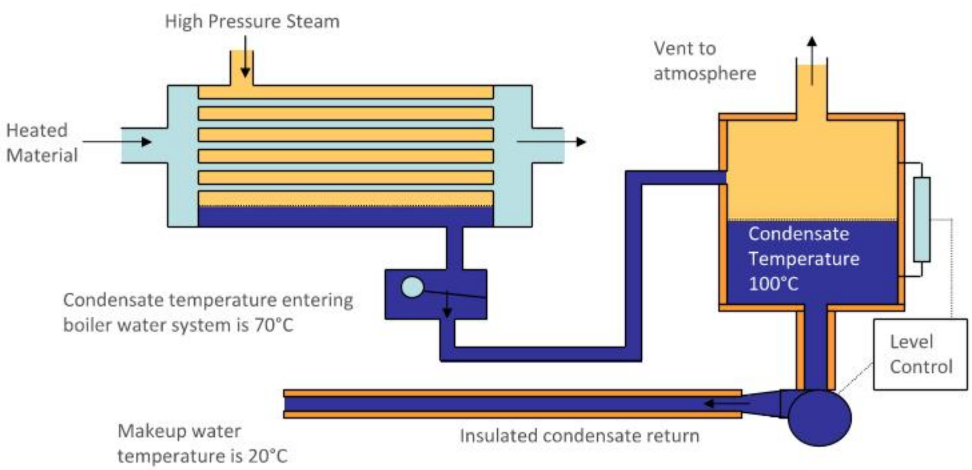
Condensate Return Example



Measured condensate temperature 100°C. Condensate flow measured by bucket and stopwatch (mass and energy balance is also a common method) to be 50 litres/minute

Source: US DOE Steam BestPractices Program

Condensate Return Example



Source: US DOE Steam BestPractices Program

Condensate Return Example

- Enthalpy of condensate: 293.1 kJ/kg
- Enthalpy of make-up: 83.9 kJ/kg
- Condensate flow rate: 50 litres/min

$\left.\begin{matrix}\\ \\\end{matrix}\right\}$ From Steam Tables

$$m_{condensate} = 50 \times 977.8 \times \frac{1}{1000} \times \frac{1}{60} = 0.81\ \frac{kg}{s}$$

$$Q_{condensate} = m_{condensate} \times \left(h_{condensate} - h_{makeup}\right)$$

$$Q_{condensate} = 0.81 \times (293.1 - 83.9) = 169.5\ kW$$

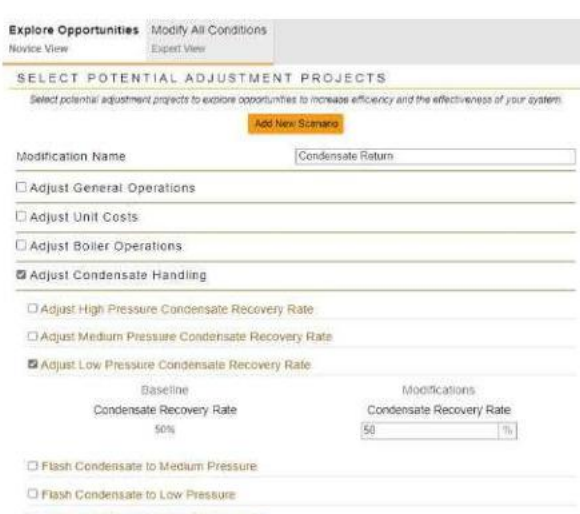
$$Q_{system} = Q_{condensate} \times \frac{1}{\eta_{boiler}} = 169.5 \times \frac{1}{0.80} = 212\ kW$$

$$Energy\ Savings = 212 \times 3{,}600 \times \frac{25}{1{,}000{,}000} \times 8{,}760 \approx \$167{,}000$$

Savings from returning condensate

Source: US DOE Steam BestPractices Program

MEASUR Assessment - Condensate Return Savings



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MEASUR Assessment – Condensate Return Savings

- Note that MEASUR requires condensate return input as a percent of steam supplied to the process at each header level
  - Manual calculations will be needed to get to the new value of condensate returned
    - Steam demand on LP = 70 Tph
    - Current condensate returned = 50%
    - Current condensate returned = 35 Tph
    - Additional condensate = 0.81 kg/s = 2.92 Tph
    - New condensate return = 35 + 2.92 = 37.92 Tph
    - New condensate return = 37.92 / 70 = 54.17%

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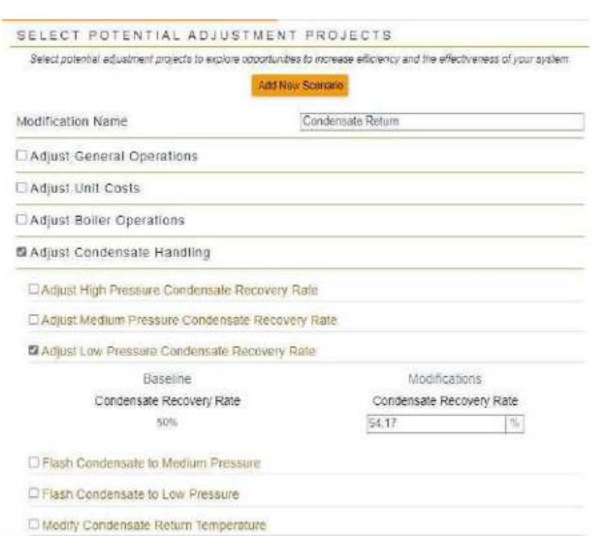
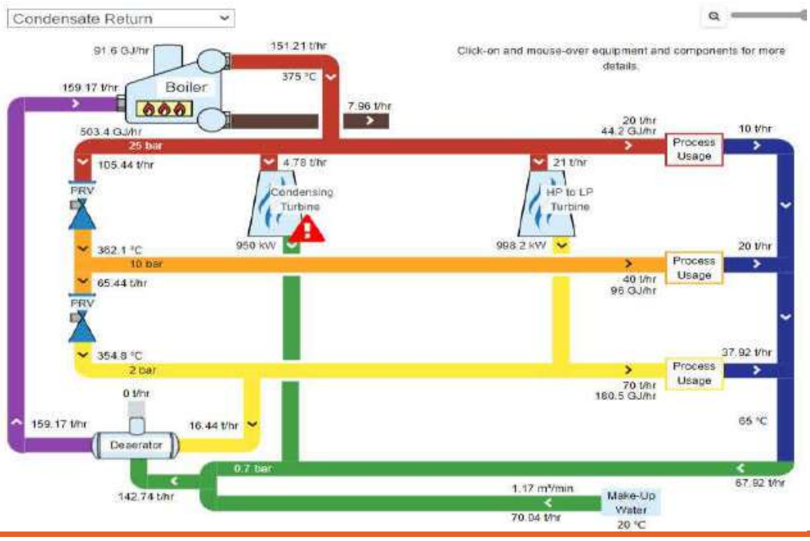


MEASUR Assessment – Condensate Return Savings



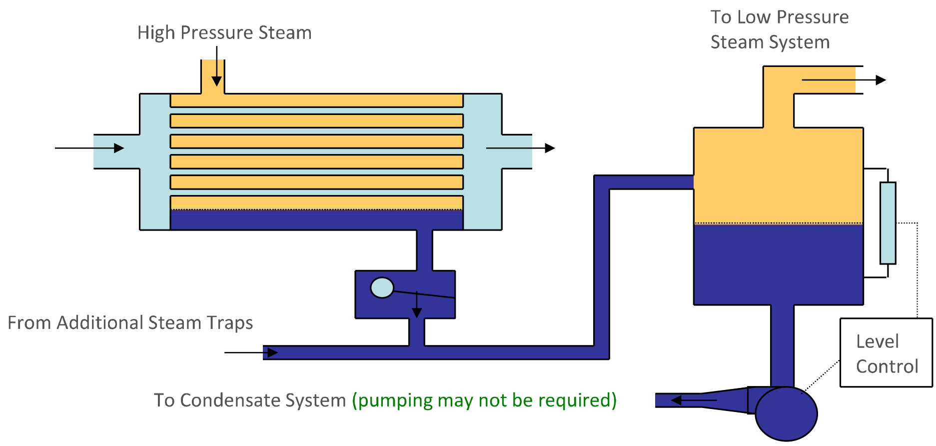
MEASUR Assessment – Condensate Return Savings

RESULTS	SANKEY	HELP

	Baseline	Condensate Return
Percent Savings (%)	——	
Fuel Usage (GJ/yr)	4,416,084	4,410,101.2
Fuel Cost ($/yr)	$110,402,099	$110,252,531
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m^3/yr)	640,361.2	614,660.2
Water Cost ($/yr)	422,638	405,676
Power Generated (kW)	1,948.2	1,948.2
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	91.7	91.6
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	43.4
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	35.9
Annual Emissions (tonne CO_2)	**222,084.86**	**221,783.99**
Annual Emissions Savings (tonne CO_2)	**—**	**300.87**
Annual Cost ($)	**115,204,737**	**115,038,207**
Annual Savings ($)	**—**	**166,531**

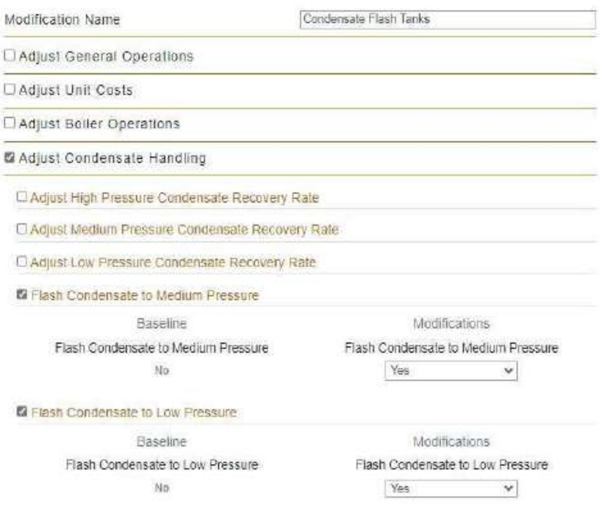
MEASUR Assessment – Condensate Return Savings

Condensate Return Example



Source: US DOE Steam BestPractices Program

MEASUR Assessment - Condensate Flash Tanks



Modification Name: Condensate Flash Tanks

☐ Adjust General Operations

☐ Adjust Unit Costs

☐ Adjust Boiler Operations

☑ Adjust Condensate Handling

☐ Adjust High Pressure Condensate Recovery Rate

☐ Adjust Medium Pressure Condensate Recovery Rate

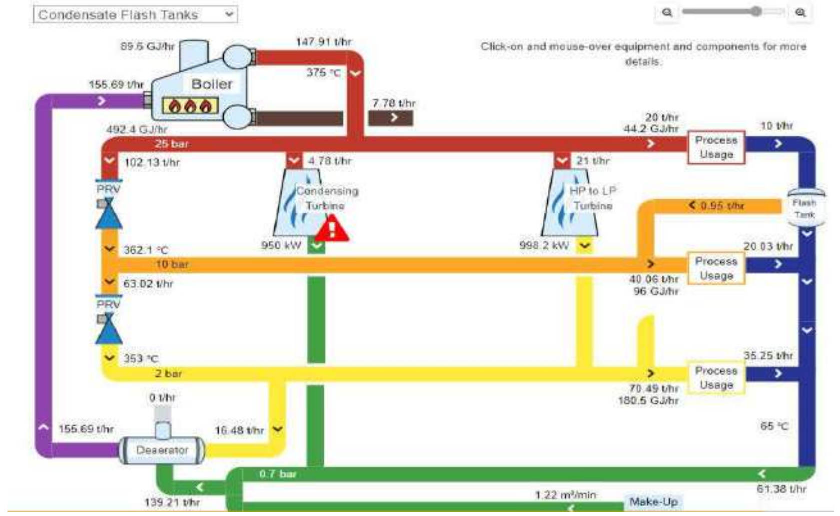
☐ Adjust Low Pressure Condensate Recovery Rate

☑ Flash Condensate to Medium Pressure

Baseline	Modifications
Flash Condensate to Medium Pressure	Flash Condensate to Medium Pressure
No	Yes

☑ Flash Condensate to Low Pressure

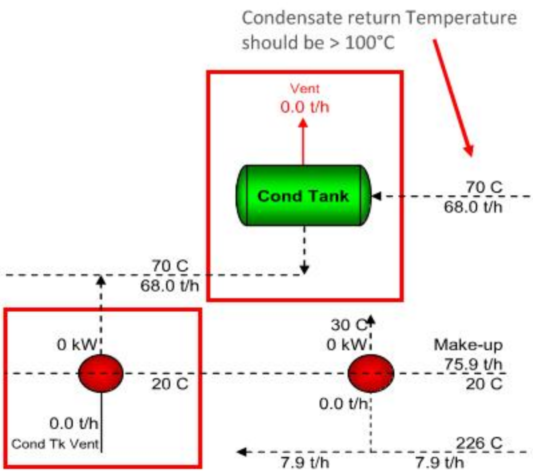
Baseline	Modifications
Flash Condensate to Low Pressure	Flash Condensate to Low Pressure
No	Yes



MEASUR Assessment - Condensate Flash Tanks

RESULTS	Baseline	Condensate Flash Tanks
Percent Savings (%)	— —	2.0%
Fuel Usage (GJ/yr)	4,416,084	4,313,704.3
Fuel Cost ($/yr)	$110,402,099	$107,842,608
Electricity Purchased (kWh/yr)	43,800,000	43,800,000
Electricity Cost ($)	4,380,000	4,380,000
Water Usage (m³/yr)	640,361.2	641,171.4
Water Cost ($/yr)	422,638	423,173
Power Generated (kW)	1,948.2	1,948.2
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	91.7	89.6
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45.2
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	25.4
Annual Emissions (tonne CO_2)	**222,084.88**	**216,936.19**
Annual Emissions Savings (tonne CO_2)	**—**	**5,148.67**
Annual Cost ($)	**115,204,737**	**112,645,781**
Annual Savings ($)	**—**	**2,558,956**

MEASUR Assessment - Condensate Flash Tanks



MEASUR Assessment – Condensate Tank Vent HX

- Note – this is possible ONLY with condensate return temperatures > 100°C
- Note – this is NOT possible right now in MEASUR due to a technical glitch but can be modeled with the Flash Tank Calculator

MEASUR Assessment – Condensate Tank Vent HX

FLASH TANK

Pressure	2	bar
Known Variable	Quality	
Quality Value	0	
Mass Flow	65	t/hr
Tank Pressure	0	bar

Generate Example | Reset Data

RESULTS | HELP

	Inlet	Steam Out	Liquid Out
Pressure (bar)	2	0	0
Temperature (°C)	133.7	100	100
Sp. Enthalpy (kJ/kg)	562.1	2,675.5	419
Sp. Entropy (kJ/kg-K)	1.673	7.354	1.307
Quality	Liquid	Gas	Liquid
Mass Flow (t/hr)	65	4.12	60.88
Energy Flow (GJ/hr)	36.5	11	25.5

Key Points / Action Items – Condensate Recovery

1. Returning condensate
    - Reduces energy
    - Reduces make-up water
    - Reduces chemicals for water treatment
    - Reduces quenching water
    - May reduce blowdown
2. Condensate recovery is often neglected but it can provide significant energy savings
3. Quantify the amount of condensate being recovered in a plant using a simple mass balance on the entire steam system
4. Identify potential areas of condensate recovery

Common BestPractices - Recovery

- Implement an effective steam-trap management and maintenance program
- Recover as much as possible of available condensate
- Recover condensate at the highest possible thermal energy
- Flash high-pressure condensate to make low-pressure steam

Source: US DOE BestPractices Steam System Sourcebook

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Section 9: Steam System Optimization – Combined Heat & Power (CHP) or Cogeneration

- BackPressure Turbine – PRV Operations
- MEASUR Turbine Projects Economics
- Condensing Turbine Impacts
- MEASUR Condensing Turbine Projects

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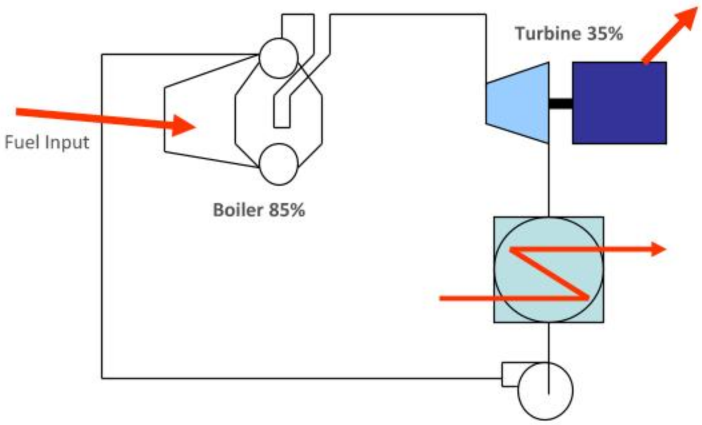

Industrial Cogeneration

- Industrial facilities can achieve "overall energy efficiency" of 70% or higher, because they have a need for thermal energy (process heat)…….

Classic Cogeneration Analysis

- The classic cogeneration analysis answers the following questions:
  - What is the true economic impact of cogeneration?
  - When is it viable?
    - To operate or shut down
    - To install
- What changes, if any, will be required on the steam system?
- What changes, if any, will be required for the electrical utility system and grid interconnects?

Primary Factors for Cogeneration Analysis

- The primary factors impacting the analysis are:
  - *Impact* electrical cost
  - *Impact* fuel cost
  - Boiler efficiency
  - Steam turbine efficiency
  - Steam demand

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Impact Costs

- *Impact* cost is the actual economic impact of increasing or decreasing electrical consumption
- The average cost of electricity is typically NOT the appropriate analysis value
- A thorough understanding of the electric rate structure is essential to evaluate the true impact of power generation systems

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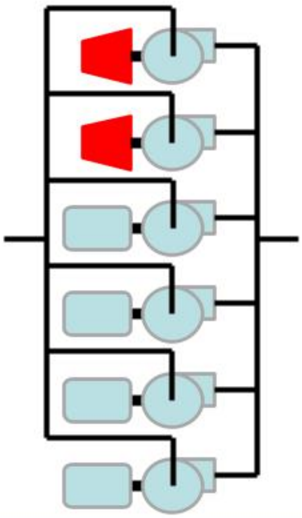
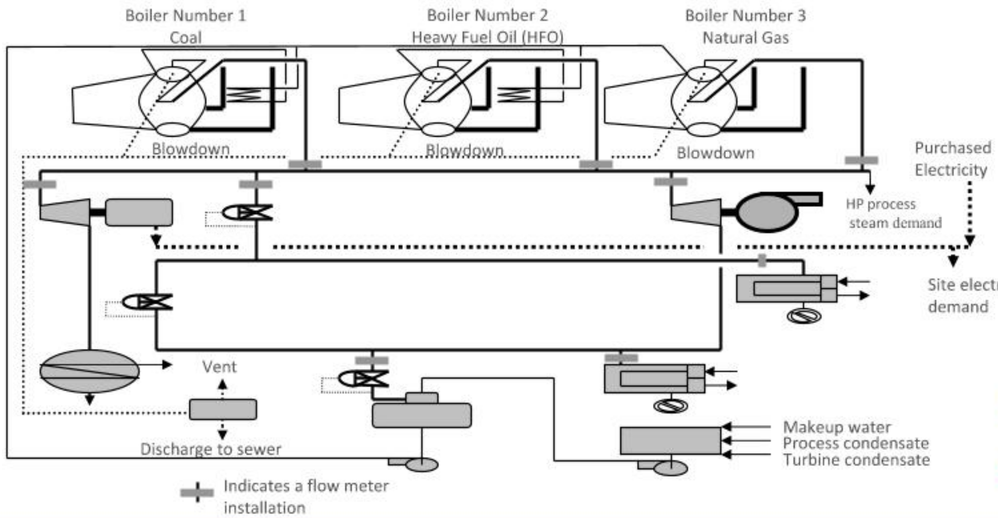


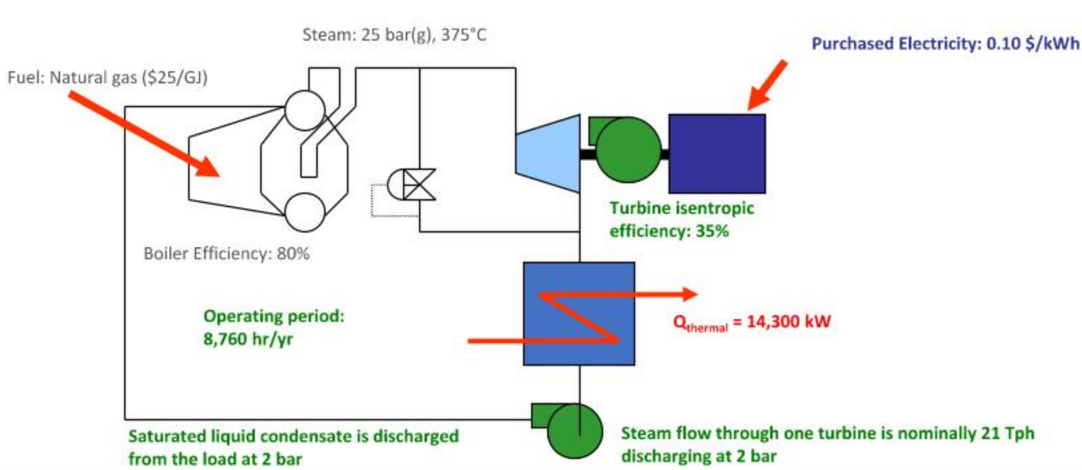
Example Turbine-PRV Evaluation

- A process unit is equipped with 6 identical pumps that are installed in parallel
  - Only 3 of the 6 pumps are required to operate continuously
    - The remaining pumps are spare (backup) units
  - Electric motors drive 4 of the pumps and steam turbines drive 2 of the pumps
    - 1 turbine-drive is being used at this time
- Identify the economic incentive associated with operating the second turbine
  - Compared to operating an electric motor driven pump and passing steam through a Pressure reducing Valve (PRV) to satisfy the low pressure demands



Steam System

Turbine-PRV Economics



PRV Operations

$$h_{steam} = 3{,}180.9\,\frac{kJ}{kg}$$ P = 25 bars; T = 375°C

$$h_{PRVout} = 3{,}180.9\,\frac{kJ}{kg}$$ P = 2 bars; Isenthalpic; T = 354.7°C

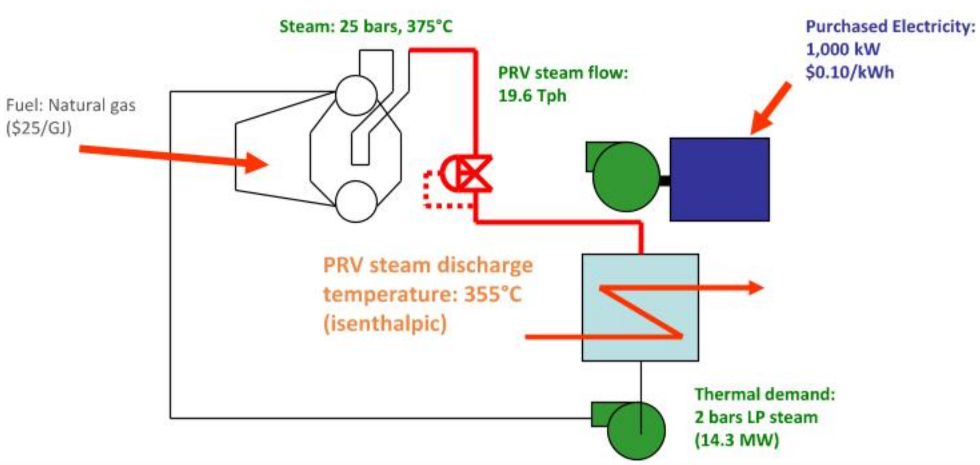
$$h_{condensate} = 562.2\,\frac{kJ}{kg}$$ P = 2 bars; Saturated Condensate; T = 133.7°C

$$Q_{thermal} = 14{,}300\ kW$$

$$Q_{thermal} = m_{PRV} \times \left(h_{PRVout} - h_{condensate}\right)$$

$$m_{PRV} = \frac{14{,}300}{\left(3{,}180.9 - 562.2\right)} = 5.45\,\frac{kg}{s} = 19.63\ Tph$$

PRV Operations



Backpressure Turbine Economics

- Most industrial systems require thermal energy (not mass flow of steam)
- The turbine will extract energy from the steam and convert it into shaft energy
  - The steam will exit the turbine with a reduced temperature
- The result will be an increased mass flow of steam required to satisfy the thermal demand

Steam Turbine Operations

$$h_{steam} = 3{,}180.9 \frac{kJ}{kg}$$ **P = 25 bars; T = 375°C**

$$h_{Turbineout} = 3{,}009.8 \frac{kJ}{kg}$$ **P = 2 bars; T = 271°C**

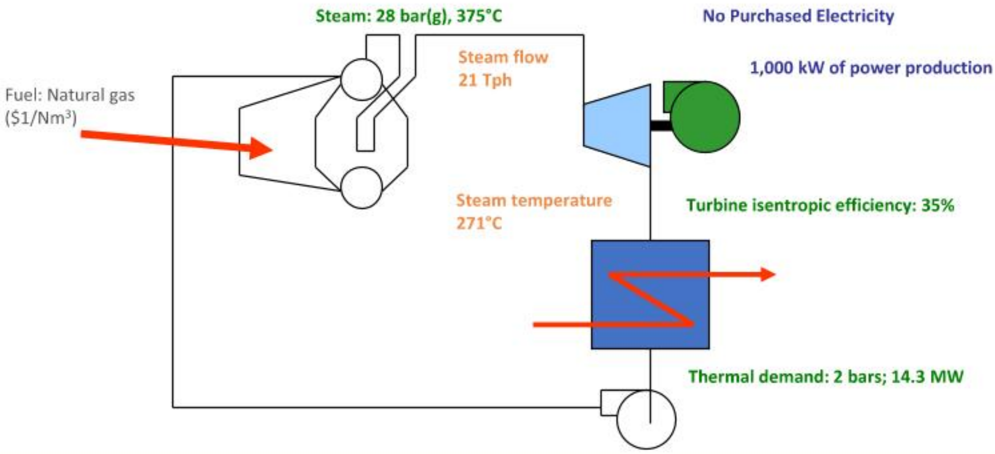
$$h_{condensate} = 562.2 \frac{kJ}{kg}$$ **P = 2 bars; Saturated Condensate; T = 133.7°C**

$$Q_{thermal} = 14{,}300\ kW$$

$$Q_{thermal} = m_{turbine} \times \left(h_{Turbineout} - h_{condensate}\right)$$

$$m_{turbine} = \frac{14{,}300}{(3{,}009.8 - 562.2)} = 5.83 \frac{kg}{s} = 21.0\ Tph$$

Steam Turbine Operation



PRV - Backpressure Turbine Economics

- Electrical Energy and Cost Savings

$$Energy\ \ Savings\ = 1{,}000 \times 8{,}760\ = 8{,}760\ MWh$$

$$Energy\ \ Cost\ \ Savings\ = 8{,}760 \times 1{,}000 \times 0.10 = \$876{,}000$$

- Fuel Energy and Cost Increase

$$Energy\ Increase = (m_{Turbine} - m_{PRV}) \times 1{,}000 \times \frac{(h_{steam} - h_{feedwater})}{\eta_{boiler}} \times 8{,}760$$

$$Energy\ Increase = (21 - 19.6) \times 1{,}000 \times \frac{(3180.9 - 463.5)}{0.80} \times 8{,}760 = 41{,}658\ GJ$$

$$Energy\ Cost\ Increase = 41{,}658 \times 25.0 = \$1{,}041{,}450$$

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PRV - Backpressure Turbine Economics

- Net Economic Impact

  $$Electric\ Power\ Cost\ Savings = \$876{,}000$$

  $$Fuel\ Cost\ Increase = \$1{,}041{,}450$$

  $$Net\ Economic\ Benefit = -\$165{,}450$$

- The primary factors impacting the analysis are:
  - *Impact* electrical cost
  - *Impact* fuel cost
  - Boiler efficiency
  - Steam turbine efficiency
  - Steam demand

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PRV - Backpressure Turbine Economics

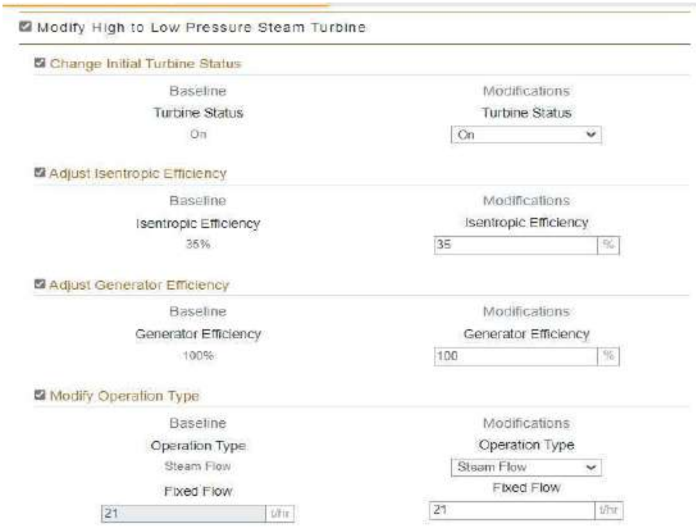
- Net Economic Impact

  $$Electric\ Power\ Cost\ Savings = \$876{,}000$$

  $$Fuel\ Cost\ Increase = \$1{,}041{,}450$$

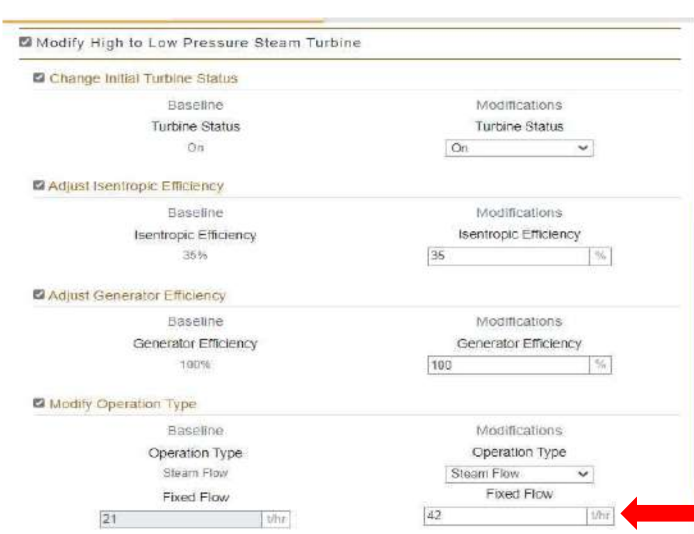
  $$Net\ Economic\ Benefit = -\$165{,}450$$

- This identical analysis can be and **should be** done with the MEASUR Assessment depending on which turbine is being modeled in the analysis
  - Systems approach versus Component-based approach



MEASUR Assessment – HP-LP Steam Turbine

- Tremendous flexibility to model steam turbine projects and their actual operations in the field



MEASUR Assessment – HP-LP Steam Turbine

Turning ON one more steam turbine – double the steam flow

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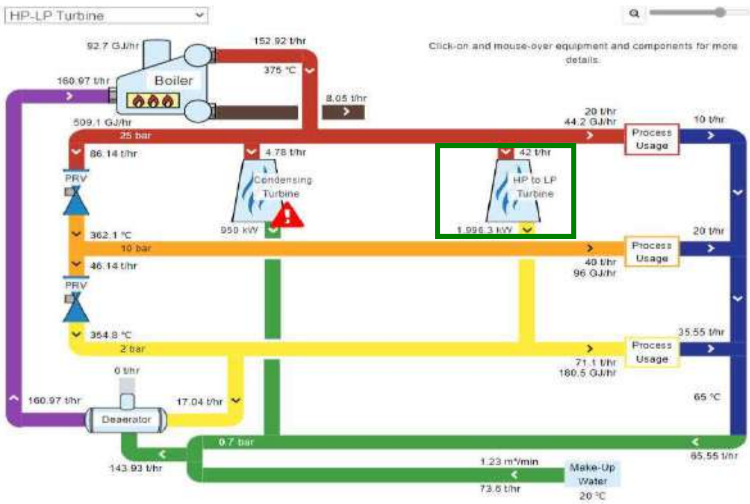

MEASUR Assessment – HP-LP Steam Turbine

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RESULTS | SANKEY | HELP

	Baseline	HP-LP Turbine
Percent Savings (%)	——	
Fuel Usage (GJ/yr)	4,416,084	4,459,820.5
Fuel Cost ($/yr)	$110,402,099	$111,495,512
Electricity Purchased (kWh/yr)	43,800,000	35,056,183.2
Electricity Cost ($)	4,380,000	3,505,618
Water Usage (m³/yr)	640,361.2	645,896.4
Water Cost ($/yr)	422,638	426,292
Power Generated (kW)	1,948.2	2,946.3
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	91.7	92.7
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45.3
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	35.3
Annual Emissions (tonne CO_2)	**222,084.86**	**220,777.49**
Annual Emissions Savings (tonne CO_2)	**—**	**1,307.37**
Annual Cost ($)	**115,204,737**	**115,427,422**
Annual Savings ($)	**—**	**-222,685**

MEASUR Assessment – HP-LP Steam Turbine

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MEASUR Assessment – HP-LP Steam Turbine

- Differences between the “Manual” versus “Model” calculated results can be significant when working with cogeneration type projects
- The Model results are very accurate
  - Uses a SYSTEM approach and not just a component
    - Impact of condensate temperature
    - Impact of blowdown, deaerator steam flow, make-up water, etc.
  - Completes a detailed mass, energy and economic balance
- ALWAYS use a SYSTEM based model for analysis

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RESULTS SANKEY HELP

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Fuel Usage (GJ/yr)	4,416,084	4,459,820.5
Fuel Cost ($/yr)	$110,402,099	$111,495,512
Electricity Purchased (kWh/yr)	43,800,000	35,056,183.2
Electricity Cost ($)	5,475,000	4,382,023
Water Usage (m^3/yr)	640,361.2	645,896.4
Water Cost ($/yr)	422,638	426,292
Power Generated (kW)	1,948.2	2,946.3
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	91.7	92.7
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45.3
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	35.3
Annual Emissions (tonne CO_2)	**222,084.86**	**220,777.49**
Annual Emissions Savings (tonne CO_2)	**—**	**1,307.37**
Annual Cost ($)	**116,299,737**	**116,303,827**
Annual Savings ($)	**—**	**-4,089**

Electrical Price Impact

- Electrical price is increased from 0.10 $/kWh to 0.125 $/kWh

RESULTS	SANKEY	HELP
	Baseline	**HP-LP Turbine**
Percent Savings (%)	— —	
Fuel Usage (GJ/yr)	4,249,831.4	4,291,921.4
Fuel Cost ($/yr)	$57,797,707	$58,370,130
Electricity Purchased (kWh/yr)	43,800,000	35,056,183.2
Electricity Cost ($)	4,380,000	3,505,618
Water Usage (m^3/yr)	640,361.2	645,896.4
Water Cost ($/yr)	422,638	426,292
Power Generated (kW)	1,948.2	2,946.3
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	72.8	73.5
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45.3
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	35.3
Annual Emissions (tonne CO_2)	**213,724.02**	**212,333.84**
Annual Emissions Savings (tonne CO_2)	**—**	**1,390.18**
Annual Cost ($)	**62,600,345**	**62,302,040**
Annual Savings ($)	**—**	**298,305**

Fuel Price Impact

- Fuel price is reduced from $25 per GJ to $13.6 per GJ
- This is representative of average fuel price for the example system – all boilers respond to demand increase/decrease equally

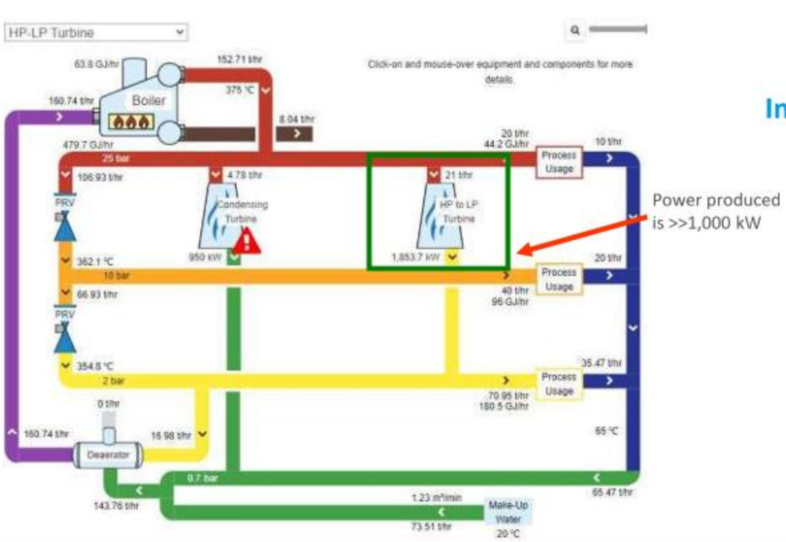
RESULTS	SANKEY	HELP
	Baseline	**HP-LP Turbine**
Percent Savings (%)	— —	2.0%
Fuel Usage (GJ/yr)	4,166,501.4	4,207,766
Fuel Cost ($/yr)	$22,499,107	$22,721,937
Electricity Purchased (kWh/yr)	43,800,000	35,056,183.2
Electricity Cost ($)	4,380,000	3,505,618
Water Usage (m^3/yr)	640,361.2	645,896.4
Water Cost ($/yr)	422,638	426,292
Power Generated (kW)	1,948.2	2,946.3
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	63.3	63.9
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45.3
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	35.3
Annual Emissions (tonne CO_2)	**373,858.06**	**208,101.67**
Annual Emissions Savings (tonne CO_2)	**—**	**165,756.39**
Annual Cost ($)	**27,301,746**	**26,653,847**
Annual Savings ($)	**—**	**647,899**

Fuel Impact

- Impact fuel is now coal at a price of $5.4 /GJ instead of Natural gas at $25.0 / GJ
- Boiler efficiency is now 86.7% (for coal) versus 81.8% (for Natural gas)

Improved Turbine Efficiency

- The isentropic turbine efficiency is now 65% instead of 35%
- What should be expected? Increase or Decrease in Operating Cost?



Improved Turbine Efficiency

- The isentropic turbine efficiency is now 65% instead of 35%
- Higher efficiency turbine extracts more power out of the steam thereby reducing steam enthalpy at the exhaust
  - Resulting in more steam to be generated by the boilers!

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RESULTS	SANKEY	HELP
	Baseline	HP-LP Turbine
Percent Savings (%)	— —	
Fuel Usage (GJ/yr)	4,166,501.4	4,201,873.9
Fuel Cost ($/yr)	$104,162,534	$105,046,848
Electricity Purchased (kWh/yr)	43,800,000	36,305,299.9
Electricity Cost ($)	4,380,000	3,630,530
Water Usage (m^3/yr)	640,361.2	645,106.9
Water Cost ($/yr)	422,638	425,771
Power Generated (kW)	1,948.2	2,803.7
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	63.3	63.8
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45.3
Turbine Losses (GJ/yr)	0.2	0.2
Other Losses (GJ/yr)	35.1	35.3
Annual Emissions (tonne CO_2)	**209,533.35**	**208,306.34**
Annual Emissions Savings (tonne CO_2)	**—**	**1,227.01**
Annual Cost ($)	**108,965,172**	**109,103,148**
Annual Savings ($)	**—**	**-137,976**

Improved Turbine Efficiency

- The isentropic turbine efficiency is now 65% instead of 35%

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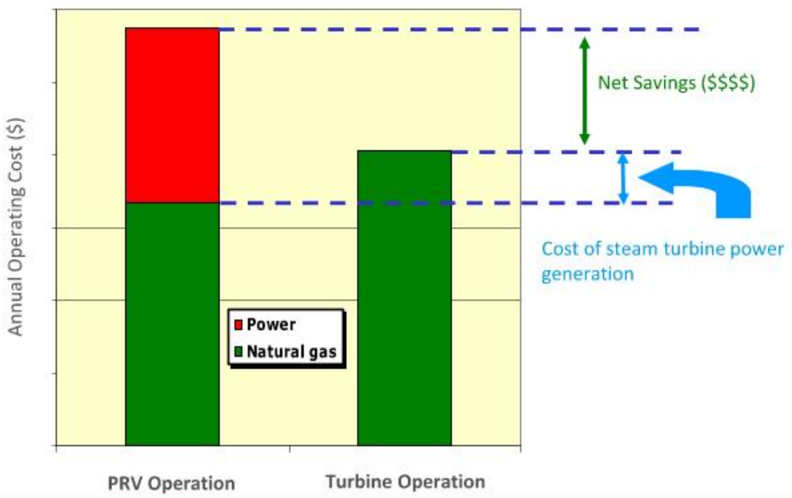
Description		Power Cost	Fuel Cost	Combustion Efficiency	Turbine Efficienc	Additional Power	Additional Steam	Net Savings
		$/kWh	$/GJ	%	%	kW	Tph	$/yr
Base Model		0.100	25.0	81.8	35.0	-	-	-
	ST Efficiency Increase	0.100	25.0	81.8	65.0	855.0	1.29	(190,948)
Added 1 ST		0.100	25.0	81.8	35.0	998.0	1.50	(222,685)
	Increased Power Cost	0.125	25.0	81.8	35.0	998.0	1.50	(4,089)
	Steam from all boilers	0.100	13.6	85.0	35.0	998.0	1.50	298,305
	Steam from coal boiler	0.100	5.4	86.7	35.0	998.0	1.50	647,899

Turbine-PRV Examples Summary Information

- These examples indicate the critical importance of impact parameter accuracy
- Each facility is unique and will need significant due diligence before implementation of these projects



Backpressure Turbine Economics

Variables for Industrial Applications

- Constant steam flow
- High pressure supply steam
- Existing Pressure Reducing Valve (PRV)
- Multiple steam header system
- Simultaneous steam and electric (power) demand
- High run hours

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Key Points / Action Items

1. Backpressure turbines are used instead of pressure letdown stations
2. Turbine efficiency is NOT 1st law efficiency but a comparison of actual turbine versus an ideal turbine
3. Continuous operations with a simultaneous thermal and electric demand are good candidates for backpressure turbines
4. Each facility analysis is unique and will depend on several economic as well as operating factors
5. Turbine analysis will need a solid thermodynamic steam system model

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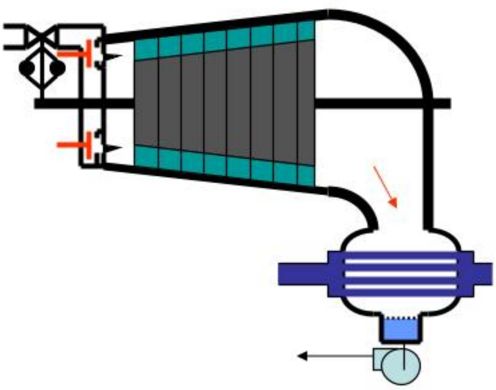
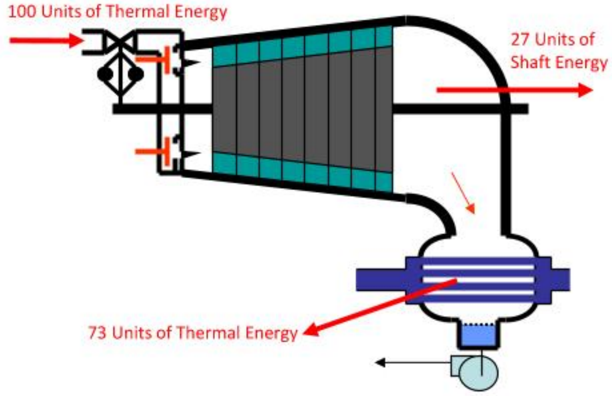


Condensing Turbine

Condensing Steam Turbines

- Condensing turbine discharge steam pressure is less than atmospheric pressure
  - The steam must be condensed to pump it back into the boiler
  - Exiting steam quality is typically much greater than 90%

Source: US DOE Steam BestPractices Program

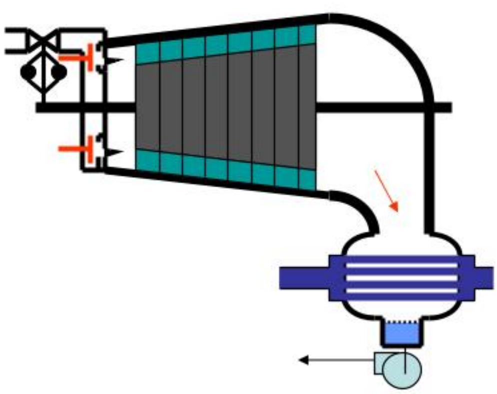


Condensing Turbine

Condensing Steam Turbines

- The steam entering the condenser contains a huge amount of fuel energy

Source: US DOE Steam BestPractices Program



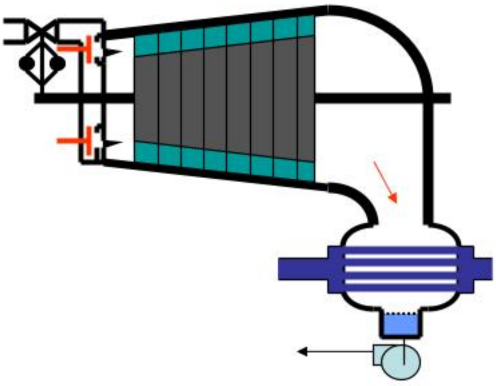
Condensing Turbine

Condensing Steam Turbines

- The primary factors influencing condensing turbine operations are:
  - Purchased power cost
  - Purchased fuel cost
  - Turbine efficiency
  - Boiler efficiency
  - Turbine discharge pressure

Source: US DOE Steam BestPractices Program

Condensing Steam Turbines

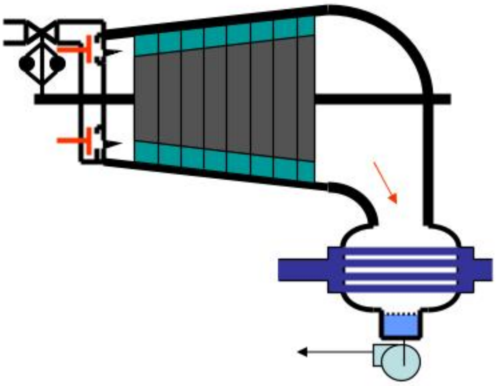


Condensing Turbine

- Efficiency reductions can result from:
  - Blade deposits
  - Blade erosion
  - Seal wear
  - Wet steam
  - Throttling
- Efficiency improvements can result from
  - Replaced blades
  - Improved seals
  - Turbine replacement
  - Increased load

Source: US DOE Steam BestPractices Program

Condensing Steam Turbines

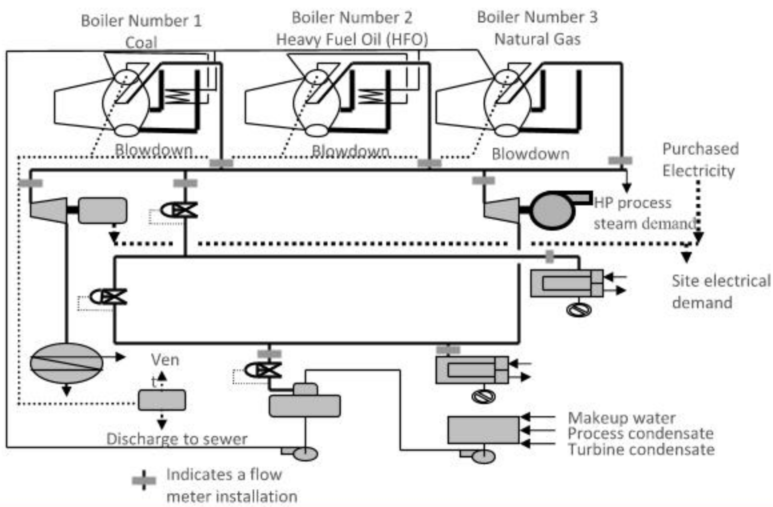


Condensing Turbine

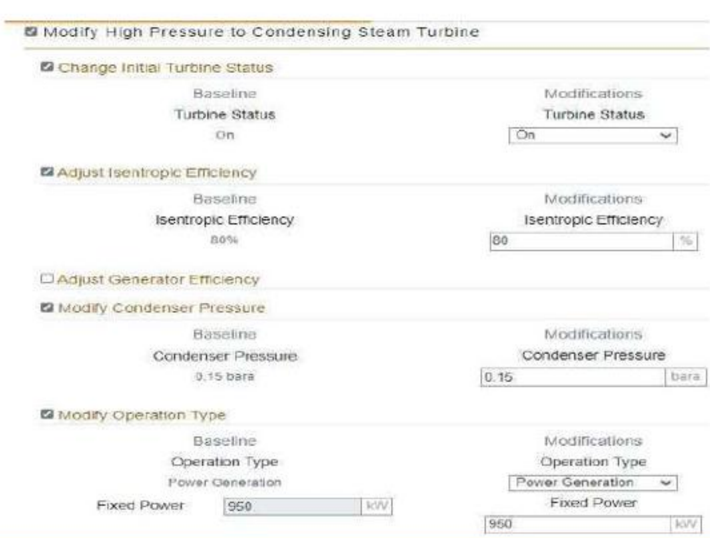
- Condenser pressure can be reduced (improved) by
  - Removing non-condensable gases from condenser
  - Cleaning the condenser
  - Supplying the condenser with reduced temperature water
  - Supplying the condenser with additional cooling water

Source: US DOE Steam BestPractices Program

Steam System

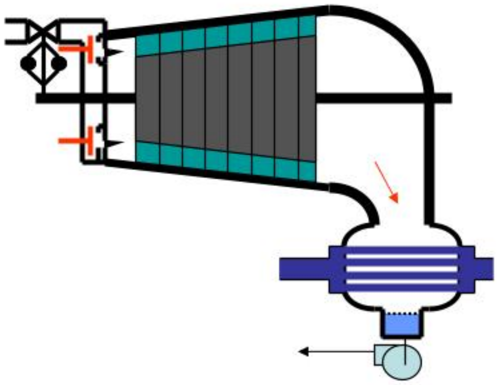


MEASUR Assessment - Condensing Steam Turbines



- Implementing MEASUR Assessment will involve a major change in steam demand
  - Be very careful while evaluating this project

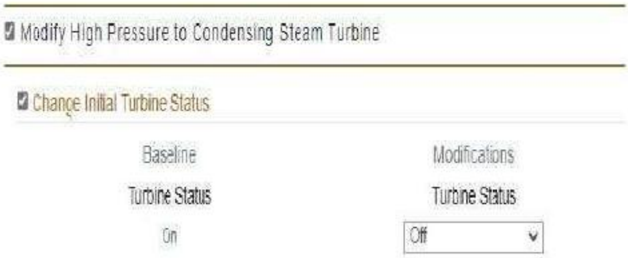
MEASUR Assessment - Condensing Steam Turbines



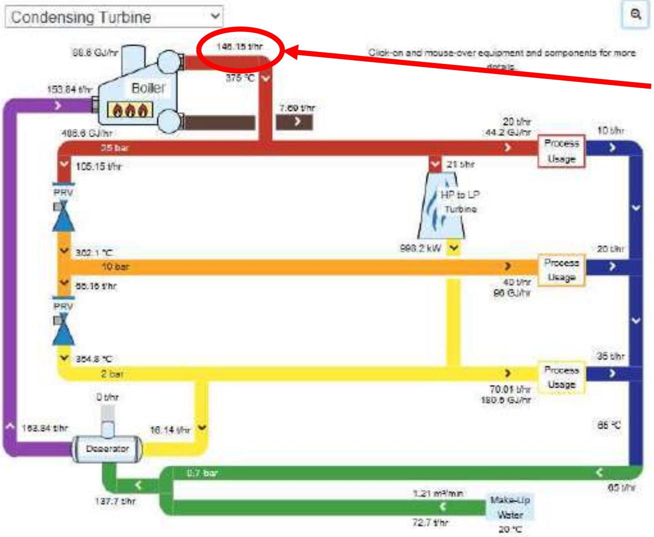
Condensing Turbine

- MEASUR allows
  - The addition of a condensing turbine
  - Modification of major aspects of an existing turbine
    - Isentropic efficiency
    - Discharge pressure
    - Load
      - Flow
      - Power
- Elimination of the operation of a turbine

MEASUR Assessment - Condensing Steam Turbines



- Impact of switching off the condensing turbine



Large change in steam flow!

MEASUR Assessment - Condensing Steam Turbines

RESULTS	Baseline	Condensing Turbine
Percent Savings (%)	— —	3.0%
Fuel Usage (GJ/yr)	4,416,084	4,252,259.6
Fuel Cost ($/yr)	$110,402,099	$106,556,490
Electricity Purchased (kWh/yr)	43,800,000	52,122,000
Electricity Cost ($)	4,380,000	5,212,200
Water Usage (m³/yr)	640,361.2	637,952.9
Water Cost ($/yr)	422,638	421,049
Power Generated (kW)	1,948.2	998.2
Process Use (GJ/yr)	320.7	320.7
Stack Loss (GJ/yr)	91.7	88.6
Vent Losses (GJ/yr)		
Unrecycled Condensate Losses (GJ/yr)	45	45
Turbine Losses (GJ/yr)	0.2	0
Other Losses (GJ/yr)	35.1	34.8
Annual Emissions (tonne CO_2)	**222,084.86**	**217,686.74**
Annual Emissions Savings (tonne CO_2)	**—**	**4,398.12**
Annual Cost ($)	**115,204,737**	**112,189,739**
Annual Savings ($)	**—**	**3,014,999**

SANKEY HELP

MEASUR Assessment - Condensing Steam Turbines

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Condensing Turbine Performance

Condensing Turbine Impact Power Cost			
Fuel Cost [$/GJ]	Impact Condensing Power Cost [$/MWh]		
	Turbine Isentropic Efficiency [%]		
	40	60	80
2.0	56	39	30
4.0	111	78	60
6.0	167	116	89
8.0	223	155	119
10.0	278	194	149
12.0	334	233	179
Steam inlet	25	bars	
Steam inlet	375	°C	
Steam exit	0.1	bar(a)	

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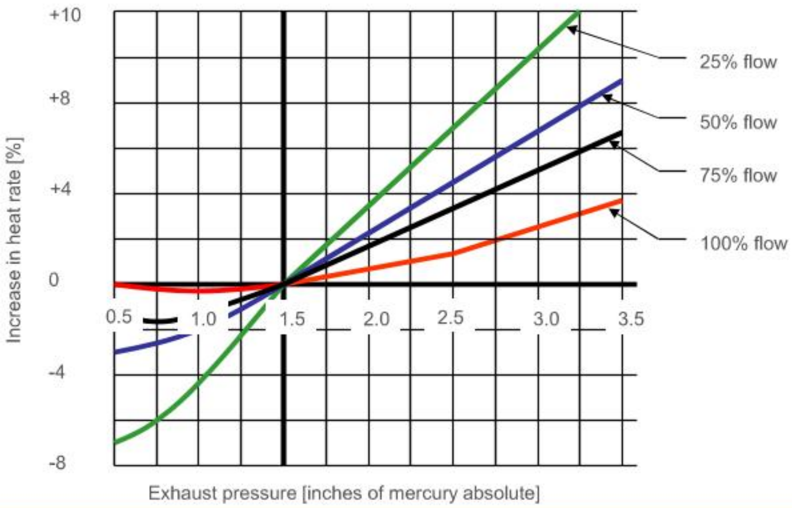
Condensing Turbine Pressure Effect

- It should be noted that a minimum pressure is generally attained where maximum energy utilization efficiency is achieved
  - In other words, there is generally a pressure threshold that further reductions in discharge pressure result in reducing overall cost effectiveness
  - Velocity losses begin to be excessive
    - This is very dependent on the turbine design
      - Larger annular steam flow area reduces the loss
  - Condensate is returned to the boiler at lower temperature
  - Common design is for 1.5 inches of mercury absolute (0.05 bara) condenser pressure



Condensing Turbine Pressure Effect

Key Points / Action Items

1. Condensing turbines are used strictly for power generation or driving large mechanical equipment
2. They serve niche applications in the industry
3. Condensing turbines provide maximum shaft power per unit of steam flow
4. Each facility analysis is unique and will depend on several economic as well as operating factors
5. Turbine analysis will need a solid thermodynamic steam system model

Common BestPractices –Turbines

- Process and utility integration leads to overall energy optimization of the plant
- Install backpressure turbines in parallel with pressure letdown stations and minimize flow through letdown stations
- Evaluate backpressure turbine applications for direct mechanical drives
- Evaluate condensing turbines and optimize their operations to maintain design conditions
- Condensing turbines can serve as a system balance mechanism especially, in industries which have significant waste heat steam generation

Source: US DOE BestPractices Steam System Sourcebook

EU – VIET NAM SUSTAINABLE ENERGY TRANSITION PROGRAMME (SETP)

Accelerating energy efficiency (EE) in larger industries through energy management system, system optimization and the promotion and adoption of EE in SMEs – (IEEP project)

Determination of boiler efficiency

UNIDO's 2-day training course on optimizing industrial steam systems for household users.

Additional compilation by: Dr. Nguyen Xuan Quang, Faculty of Thermal Energy, School of Mechanical Engineering, Hanoi University of Science and Technology

Contents

Determination of boiler efficiency according to TCVN 8630-2019

- Types of fuel used in Vietnam
- Fuel heating value, concepts and influencing factors.
- Vietnam Standard TCVN 8630-2019 and what you need to know.
- Direct method of efficiency, indirect method of efficiency.
- Flue gascomponents and how to determine
- Dry oxygen, wet oxygen, concept and method of conversion.
- Losses due to flue gas
- Other losses.

Fuel used for industrial boiler

Fuel used


Mùn cưa


Bột gỗ


Dăm bào


Vỏ trấu


Viên nén từ cây keo


Viên nén từ vỏ trấu


Viên nén từ gỗ tràm nước


Viên nén từ bã mía

Fuel used for industrial boilers

- Types of fuel used


Củi thanh


Củi gỗ băm


Crushed rice husk


Coffee bean skin


Củi trấu (củi mùn cưa)


Gỗ chẻ cục


Gỗ vụn chu kỳ ngắn


Rơm rạ


Lõi ngô


Cashew nut skin

The composition of the fuel

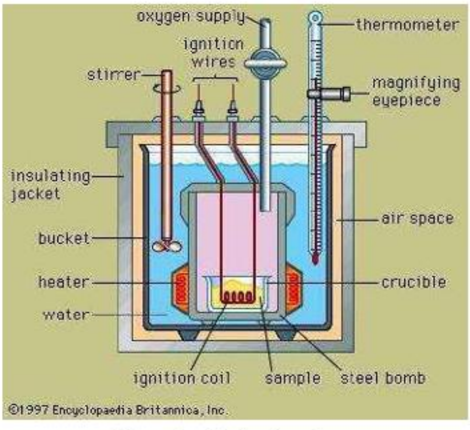
- Ultimate analysis:
  - There are 5 chemical components including: C, H, O, N, S, Ash (A), Moisture (M) in which C, H, S are combustible components that generate heat.
  - The heat generated by the combustion of a fuel is due to the % C, H, S of the fuel more or less.
  - Combustion reaction: $C + O_2 = CO_2$; $H_2 + 1/2O_2 = H_2O$; $S + O_2 = SO_2$
- Proximate analysis:
  - There are 4 components including, ash, moisture, volatile matter (V), the fixed carbon represent the combustible characteristics of the fuel.

$$C+H+O+N+S+A+M=100\%$$
$$A+M+V+C=100\%$$

- Laboratories can now easily determine the Ultimate analysis as well as Proximate analysis of fuels

Fuel heating value

- Fuel heating value. Energy contained in 1 unit mass of fuel is given in kJ/kg; kCal/kg; Btu/lb etc.
  - High heating value: Higher Heating Value (HHV) or Gross Calorific value (GCV) is the fuel heating value assuming that all the amount of water vapor formed during combustion is condensed and the amount of heat generated during that condensation is included in the heating value.
  - Low heating Value (LHV) or Net Calorific Value (NCV) is the fuel heating value with the explanation that all the amount of water vapor formed during combustion is not condensed and that the amount of heat released by condensation is lost.
  - Heating value is also divided according to concepts such as isobaric heating value, isometric, dry sample, working sample.
  - The distinction between the heating values of a fuel is necessary to evaluate a fuel and to serve as a basis for determining the performance of equipment that converts energy from fuel.



Bomb Calorimeter

Fuel heating value

- The heating value when analyzed in the laboratory is high heating value, isometric, dry sample.
- The heating value when burning in the furnace is low heating value, isobaric, working sample (with moisture).
- Efficiency can be calculated based on high heating value or low heating value, whereby if calculated based on high heating value, the efficiency value will be lower and when calculated based on low heating value, the efficiency value will be higher.

Fuel analysis according to national standards TCVN 200:2011

- The heating value when analyzed in a calorimeter bomb usually gives us the value of the high heating value of the dry sample (often called the total heating value) denoted by $q_{v.gr.m}$
- Convert this heating value to high heating value according to the working sample according to the formula.

$$q_{v.gr.m} = q_{v.gr.d}(1-0,01M_T)\ (J/g)$$

- Where MT is the humidity of the working sample(%)
- Convert to low heating value working according to the formula

$$q_{p.net.m}=\{q_{v.gr.d} - 212H_d-0,8(O_d+N_d)\}(1-0,01M_T)-24.43M_T$$

Or

$$q_{p.net.m}=q_{v.gr.m} - 212H_T-0,8(O_T+N_T)-24.43M_T$$

Where the symbols d: dry; T: actual; gr: high; Net: low. p: isobaric; V: isometric. Unit of H,O,N content in (%)

Example

Perform calculations with the following values:

Total moisture content: 8,9% (Sample received)

Moisture content in the analytical sample: 2,5% (Air dry sample)

Total Heating value, at constant volume27 230 J/g (Dry Sample heatingValue)

Hydro 4,19% (dry sample)

oxy : 6,81% (dry sample)

nitơ 1,45% (dry sample)

The Low heating value at constant pressure can be determined as follows:

a) in a dry state

$q_{p.net.dry}$ = [27 230 – (212 x 4,19) – 0,8 (6,81 + 1,45)] x [1 – (0,01 x 0)] – (24,43 x 0) = [27 230 – 888,28 – (0,8 x 8,26)] x 1 – 0 = (27 230 – 888,28 – 6,608) x 1= 26340 J/g

b) in the receiving sample

$q_{p.net.as\text{-}received}$ = [27 230 – (212 x 4,19) – 0,8 (6,81 + 1,45)] x [1 – (0,01 x 8,9)] – (24,43 x 8,9) = [27 230 – 888,28 – (0,8 x 8,26)] x (1 – 0,089) – 217,427 = (27 230 – 888,28 – 6,608) x 0,911 – 217,427= 26 335,112 x 0,911 – 217,427= 23 770 J/g

c) in an air-dry state

$q_{p.net.air\text{-}dried}$ = [27 230 – (212 x 4,19) – 0,8 (6,81 + 1,45)] x [1 – (0,01 x 2,5)] – (24,43 x 2,5)= [27 230 – 888,28 – (0,8 x 8,26)] x (1 – 0,025) – 61,075= (27 230 – 888,28 – 6,608) x 0,975 – 61,075= 26 335,112 x 0,975 – 61,075= 25 676,734 - 61,075= 25 620 J/g

Notes

1cal/g = 4,1868 J/g 1j/g = 0.2388 cal/g

1btu/lb = 2.326 J/g 1J/g = 0.4299btu/lb

National standard on energy yield and test method TCVN 8630-2019

- Applicable to boilers in Vietnam
- Issued in 2019 to replace TCVN 8630 - 2010 standard
- The minimum performance regulation has more detailed cases with 5 savings levels
- The performance test method follows both forward and reverse equilibrium and does not stipulate a minimum test time.

TCVN 8630:2019

Fuel types	Energy efficiency level	Boiler Capacity D, t/h		
		D < 3	3 ≤ D ≤ 15	D > 15
		Energy efficiency %		
Coal	Level 1	76	82	85
	Level 2	73	78	82
	Level 3	70	75	78
	Level 4	68	72	75
	Level 5	65	70	72
Biomass	Level 1	75	78	82
	Level 2	73	76	78
	Level 3	70	73	75
	Level 4	68	70	72
	Level 5	65	68	70
Requirements for equipping the flue gas heat recovery unit of the boiler itself		Optional	Encourage	Compulsory

Fuel types	Energy efficiency level	Boiler Capacity D, t/h		
		D < 3	3 ≤ D ≤ 15	D > 15
		Energy efficiency %		
Oil	Level 1	88	90	92
	Level 2	84	88	90
	Level 3	82	85	88
	Level 4	80	82	85
	Level 5	78	80	82
gas	Level 1	88	91	94
	Level 2	85	89	92
	Level 3	82	87	90
	Level 4	81	85	87
	Level 5	80	83	85
Requirements for equipping the flue gas heat recovery unit of the boiler itself		Optional	Encourage	Compulsory

TCVN 8630:2019

- Level 1: Energy saving level type 1.
- Level 2: Energy saving level type 2.
- Level 3: The minimum applies to new boilers and no more than 2 years of operation.
- Level 4: The minimum applies to boilers that have been operating for more than 2 years to less than 10 years.
- Level 5: The minimum applies to boilers that have been in operation for 10 years or more.

Boiler efficiency based on direct efficiency

Boiler that produce saturated steam

$$\eta = \frac{D_{\Sigma}\left(h_h - h_{nc}\right)}{B_{\Sigma} Q_t^{lv}}.100\%$$

Boiler that produce superheated steam and reheated steam

$$\eta = \frac{D_{\Sigma}\left(h_h - h_{nc}\right) + D_{\Sigma}^{tqn}.\left(h_{tqn}^{"} - h_{tqn}^{'}\right)}{B_{\Sigma} Q_t^{lv}}.100\%$$

- It is necessary to measure the amount of steam produced (through a supply water meter or steam meter)
- It is necessary to determine the amount of fuel consumed (operation management determines the number of vehicles/buckets of fuel used.
- Fuel Heating value (fuel moisture analysis and management) should be determined

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Boiler efficiency by indirect method (TCVN 8630 - 2019)

- Boiler efficiency according to indirect method is determined from the determination of heat losses:

$$\eta_n = 100 - \left(q_2 + q_3 + q_4 + q_5 + q_6\right) \quad \%$$

Trong đó:

- q_2 is the heat loss due to the flue gas from the boiler, %;
- q_3 is heat loss due to incomplete chemical combustion, %;
- q_4 is a heat loss due to incomplete mechanical combustion, %;
- q_5 is a heat loss due to heat dissipation to the surrounding environment, %;
- q_6 is heat loss due to heat of slag, %.

Determination of the theoretical components of flue gas

- Theoretical composition = composition produced when completely combustible, not lacking is determined based on chemical reactions and analytical chemical composition of the fuel.

$$C + O_2 = CO_2$$
$$H_2 + 1/2O_2 = H_2O$$
$$S + O_2 = SO_2$$

- Theoretical components contained in flue gas will include::
  - CO_2 from carbon combustion
  - H_2O from the combustion of Hydrogen, from the moisture component in the fuel, from the moisture present in the air introduced into combustion
  - SO_2 from combustion Sulfur,
  - N_2: from the incoming air and N in the fuel

Determination of components in theoretical flue gas

Component	By standard volume (Nm3/kg of fuel)
Stoichiometric air	$V^0_{kk} = 0{,}0889(C + 0{,}375S) + 0{,}265H – 0{,}033O$
Water vapor in flue gas formed by burning Hydrogen Fuel	$0.111H$
Water vapor formed due to moisture from fuel	$0.0124\ M$
Water vapor forms due to moisture in the air	$0.00402\ d\ V^0_{kk}$
Theoretical steam in flue gas	$V^0_{H2O} = 0.111H + 0.0124M + 0.0402V^0_{kk}$
Theoretical nitrogen in flue gas	$V^0_{N2} = 0.79\ V^0_{kk} + 0.008N$
Theoretical RO2 (RO2 is an integration of CO2 and SO2)	$V^0_{RO2} = 0.01886(C+0.375S)$
Theoretical dry flue gas	$V^0_{khói\ khô} = V^0_{N2} + V^0_{RO2}$
Theoretical flue gas	$V^0_{khói} = V^0_{khói\ khô} + V^0_{H2O}$

Notes: m^3_{tc} is a unit of volume calculated under standard conditions of 0°C and 1 atmosphere whereby 1mol = 22.4 standard liters or 1kmol = 22.4 m3tc.

Air moisture content d in g of water vapor / kg of dry air can be easily determined when knowing the relative humidity and ambient air temperature according to software or mobile apps.

Actual air and actual components in flue gas

- The combustion process needs to supply an amount of air more than the theoretical amount of air. The excess air coefficient is a coefficient representing the ratio of actual air to theoretical air according to the formula:

$$\alpha = \frac{V_{kk}^{tt}}{V_{kk}^{0}}$$

- The excess air ratio is a coefficient representing the ratio of excess air to theoretical air:

$$\lambda = \frac{V_{kk}^{thừa}}{V_{kk}^{0}} \text{ where as } \alpha = \frac{V_{kk}^{tt}}{V_{kk}^{0}} = \frac{V_{kk}^{thừa} + V_{kk}^{0}}{V_{kk}^{0}} = \lambda + 1$$

- This greater amount of air is what led flue gas analysis to see the oxygen content present in the flue gas.
- Excess air will lead to an increase in losses due to flue gas Q2 that reducing boiler efficiency.
- The determination of the amount of excess air is calculated based on the measurement of the flue gas oxygen content.

Dry oxygen – Wet oxygen

Dry oxygen: Determined when the measuring device draws flue gas into the instrument. This flue gas is passed through the filtration and separation equipment system before coming into contact with sensors that determine the content. The % composition of dry oxygen is therefore determined by dry flue gas. Most portable measuring devices used for flue gas analysis result in dry oxygen.

$$\%O_2^{khô} = \frac{V_{O2}}{V_{khói\ khô}}$$

Wet oxygen: is determined when the sensor of the measuring device is in direct contact with the actual flue gas and gives results. The % composition of wet oxygen is therefore determined by moisture flue gas. Most measuring devices are permanently installed at the factory to control the combustion process as a result of wet oxygen.

$$\%O_2^{ướt} = \frac{V_{O2}}{V_{khói\ ẩm}} = \frac{V_{O2}}{V_{khói\ khô} + V_{H2O}}$$

Dry oxygen – Wet oxygen

From dry oxygen calculates the coefficient of excess air and wet oxygen	
Excess air ratio	$\lambda = \frac{\%O_2^{khô} V^0_{khói\ khô}}{(0{,}2095 - \%O_2^{khô})V^0_{kk}}$
Excess air coefficient	$\alpha = \lambda + 1 = \frac{\%O_2^{khô} V^0_{khói\ khô}}{(0{,}2095 - \%O_2^{khô})V^0_{kk}} + 1$
Dry/wet oxygen ratio	$\frac{\%O_2^{khô}}{\%O_2^{ướt}} = \frac{V^0_{khói\ ẩm} + V^0_{kk}\lambda}{V^0_{khói\ khô} + V^0_{kk}\lambda}$
Wet oxygen	$\%O_2^{ướt} = \frac{\%O_2^{khô}(V^0_{khói\ khô} + V^0_{kk}\lambda)}{V^0_{khói\ ẩm} + V^0_{kk}\lambda}$

From wet oxygen, calculate the coefficient of excess air and dry oxygen	
Excess air ratio	$\lambda = \frac{\%O_2^{ướt} V^0_{khói\ ẩm}}{(0{,}2095 - \%O_2^{ướt})V^0_{kk}}$
Excess air coefficient	$\alpha = \lambda + 1 = \frac{\%O_2^{ướt} V^0_{khói\ ẩm}}{(0{,}2095 - \%O_2^{ướt})V^0_{kk}} + 1$
Dry/wet oxygen ratio	$\frac{\%O_2^{khô}}{\%O_2^{ướt}} = \frac{V^0_{khói\ ẩm} + V^0_{kk}\lambda}{V^0_{khói\ khô} + V^0_{kk}\lambda}$
Dry oxygen	$\%O_2^{khô} = \frac{\%O_2^{ướt}(V^0_{khói\ ẩm} + V^0_{kk}\lambda)}{V^0_{khói\ khô} + V^0_{kk}\lambda}$

In some documents, the excess air coefficient is calculated using the simple formula below without determining whether the measured oxygen is dry or wet. The result of the calculation therefore has certain deviations

$$\alpha = \frac{V^{tt}_{kk}}{V^0_{kk}} = \frac{\%O_2}{21 - \%O_2}$$

The amount of flue gas and the amount of flue gas loss

- Actual Flue gas

$$V^{thực}_{khói\ khô} = V^0_{khói\ khô} + V^{thừa}_{kk}$$
$$V^{thực}_{khói\ ẩm} = V^0_{khói\ ẩm} + V^{thừa}_{kk}$$

- Heat loss due to Flue gas

$$Q_2 = (I_{khói} - V_{kk}(ct)_{kkl}(100 - q_4) \qquad \text{(kJ/kg nhiên liệu)}$$

$$q_2 = \frac{Q_2}{Q_t^{lv}} = \frac{(I_{khói} - V_{kk}(ct)_{kkl}(100 - {}_4)}{Q_t^{lv}} \qquad \%$$

Description	Calculation formula
Enthalpy of RO2 composition (including CO2 and SO2)	$I_{RO2} = V^0_{RO2}(ct)_{RO2}$
Enthalpy of the N2 component	$I_{N2} = V^0_{N2}(ct)_{N2}$
Enthalpy of H2O composition	$I_{H2O} = V^0_{H2O}(ct)_{H2O}$
Enthalpy of air	$I_{kk} = V^0_{kk}(ct)_{kk}$
Enthalpy of theoretical dry flue gas composition	$I^0_{khói\ khô} = I_{RO2} + I_{N2}$
Enthalpy of moist flue gas composition	$I^0_{khói} = I_{RO2} + I_{N2} + I_{H2O}$
Enthalpy of dry flue gas (with excess air)	$I_{khói\ khô} = I^0_{khói\ khô} + (\alpha - 1)I_{kk}$
Enthalpy of flue gas with excess air	$I^0_{khói} = I^0_{khói} + (\alpha - 1)I_{kk} + 0.0402(\alpha - 1)I_{H2O}$

Table of specific heat capacity of flue gas components

Temperature, ^0C	$(Ct)_{kk}$, kJ/Nm³	$(Ct)_{RO2}$, kJ/Nm³	$(Ct)_{N2}$, kJ/Nm³	$(Ct)_{H2O}$, kJ/Nm³	$(Ct)_{tro}$, kJ/kg
100	129,95	170,03	129,58	151,02	81,0
200	261,24	357,46	259,92	304,46	169,8
300	394,89	558,81	392,01	462,72	264,0
400	531,20	771,83	526,52	626,16	360,0
500	670,90	994,35	683,80	794,85	458,0
600	813,36	1224,66	804,12	968,88	560,0
700	958,86	1431,07	947,52	1148,84	662,5
800	1090,56	1704,88	1093,60	1334,40	768,0
900	1256,94	1952,28	1239,84	1526,13	825,0
1000	1408,70	2203,50	1391,70	1722,90	985,0
1100	1562,55	2458,39	1513,74	1925,11	1092,0
1200	1718,16	2716,56	1697,16	2132,28	1212,0
1300	1874,86	2976,74	1852,76	2343,64	1360,0
1400	2032,52	3239,04	2028,72	2559,20	1585,0
1500	2191,68	3503,10	2166,00	2779,05	1758,0
1600	2351,68	3768,80	2324,48	3001,76	1880,0
1700	2512,26	4035,31	2484,04	3229,32	2065,0
1800	2674,26	4304,70	2643,66	3458,34	2185,0
1900	2836,32	4573,98	2804,02	3690,57	2385,0
2000	3000,00	4814,20	2965,00	3925,60	2514,0
2100	3163,02	5115,39	3127,32	4163,04	2640,0
2200	3327,50	5386,48	3289,22	4401,98	2762,0
2300	3492,08	5658,46	3452,30	4643,47	-
2400	3658,08	5930,40	3615,36	4887,60	-

The process of determining exhaust flue gas losses on excel tools

Table 1. Fuel composition by mass %			
Fuel composition	**Symbol**	**Unit**	**Value**
Carbon	Clv	%	35.81
Hydrogen	Hlv	%	3.83
Nitrogen	Nlv	%	0.4
Sulfur	Slv	%	0.04
Oxygen	Olv	%	30.31
Humidity	W	%	29.46
Ashes	A	%	0.15
Total		%	**100.00**
Low heating value working sample	Q^{lv}_t	kJ/kg	**12150**

- Enter the analyzed fuel specifications according to table 1 here

Table 2. Calculation of the moisture content of the air			
Fuel composition	**Symbol**	**Unit**	**Value**
Dry bulb temperature	Tdb	oC	30
Wet bulb temperature	Twb	oC	
Relative humidity	Rhm	%	76
Atmospheric pressure		pa	101300
Calculation factor Saturation	C1		610.7
Calculation factor Saturation	C2		44.445
Calculation factor Saturation	C3		1.4131
Calculation factor Saturation	C4		0.02763
Calculation factor Saturation	C5		0.00026
Calculation factor Saturation	C6		2.9E-06
Saturation pressure of water vapor at dry bulb temperature (Tdb)	PsWvTdb	Pa	4241.511
Water vapor partial pressure in humid air	PpWvA	Pa	3223.548
Humidity in dry air	MFrWDA	kg/kg	0.0204
Humidity in dry air		g/kg	20.44

The determination of moisture content can be in different ways.
Ability to use app : Calculator of Air

- Table 2 for determining the moisture content of ambient air

The process of determining exhaust flue gas losses on excel tools

Table 3. Calculation of the products of theoretical combustion of fuel				
Types of products	Values in Nm^3/kg of fuel			
	Symbol	Unit	Equation	Value
Stoichiometric Air	V^0_{kk}	Nm^3/kg of fuel	$V^0_{kk} = 0,0889(C + 0,375S) + 0,265H - 0,033O$	3.20
Air moisture content	d	Nm^3/kg of fuel	*Lấy số liệu từ bảng 2*	20.44
Water vapor in Flue gas due to Hydrogen Fuel	$V^0_{H2O}1$	Nm^3/kg of fuel	0.111*H	0.43
Water vapor formed due to moisture from fuel	$V^0_{H2O}2$	Nm^3/kg of fuel	0.0124*W	0.37
Water vapor formed by moisture from the air	$V^0_{H2O}3$	Nm^3/kg of fuel	$0.00161*d*V^0_{kk}$	0.11
Theoretical steam in Flue gas	V^0_{H2O}	Nm^3/kg of fuel	$V^0_{H2O} = 0.111H + 0.0124W + 0.00161dV^0_{kk}$	0.90
Theoretical nitrogen in Flue gas	V^0_{N2}	Nm^3/kg of fuel	$V^0_{N2} = 0.79\ V^0_{kk} + 0.008N$	2.53
Theoretical CO2	V^0_{CO2}	Nm^3/kg of fuel	0.01866C	0.668
SO2 theory	V^0_{SO2}	Nm^3/kg of fuel	0.007S	0.000
RO2 theory	V^0_{RO2}	Nm^3/kg of fuel	$V^0_{RO2} = 0.01866(C+0.375S)$	0.6685
Theoretical dry Flue gas	$V^0_{khói\ khô}$	Nm^3/kg of fuel	$V^0_{khói\ khô} = V^0_{N2} + V^0_{RO2}$	3.1993
Theoretical Flue gas	$V^0_{khói\ ẩm}$	Nm^3/kg of fuel	$V^0_{khói\ ẩm} = V^0_{khói\ khô} + V^0_{H2O}$	4.0951

- Table 3 will automatically calculate the theoretical volumetric components of air and flue gas components

The process of determining exhaust flue gas losses on excel tools

Table 4. From wet oxygen, calculate the coefficient of excess air and dry oxygen				
Description	Symbol	Unit	Equation	Value
Wet oxygen	$O_2^{ướt}$	-	Đo được bằng sensor tiếp xúc trực tiếp với khói	0.1335
Denominator	-	-	$(0.2095 - O_2^{ướt})*V^0_{kk}$	0.24
excess air ratio	λ	-	$\lambda = \frac{O_2^{ướt} V^0_{khói\ ẩm}}{(0,2095 - O_2^{ướt})V^0_{kk}}$	2.25
Coefficient of excess air	α	-	$\alpha = \frac{O_2^{ướt} V^0_{khói\ ẩm}}{(0,2095 - O_2^{ướt})V^0_{kk}} + 1$	3.25
Numerator	—	-	$V^0_{khói} + \lambda * V^0_{kk}$	11.29
Denominator	—	-	$V^0_{khói\ khô} + V^0_{kk} * \lambda$	10.39
Dry/wet oxygen ratio	-	-	$\frac{O_2^{khô}}{O_2^{ướt}} = \frac{V^0_{khói\ ẩm} + V^0_{kk}\lambda}{V^0_{khói\ khô} + V^0_{kk}\lambda}$	1.09
Dry oxygen	$O_2^{khô}$	-		0.14501

- Table 4 is used to determine the excess air coefficient when the measured oxygen value is wet oxygen. Can be converted to dry oxygen if needed

The process of determining exhaust flue gas losses on excel tools

Table 5. Knowing dry oxygen calculates the coefficient of excess air and wet oxygen				
Description	**Symbol**	**Unit**	**Equation**	**Value**
Dry oxygen	$O_2^{khô}$	-	Đo được bằng cách hút khói vào thiết bị đo (testo)	0.145
Denominator	-	-	$(0.2095 - O_2^{khô})*V^0_{kk}$	0.21
excess air ratio	λ	-	$\lambda = \frac{\%O_2^{khô} V^0_{khói\ khô}}{(0{,}2095 - \%O_2^{khô})V^0_{kk}}$	2.25
Coefficient of excess air	α	-	$\alpha = \lambda + 1 = \frac{\%O_2^{khô} V^0_{khói\ khô}}{(0{,}2095 - \%O_2^{khô})V^0_{kk}} + 1$	3.25
Numerator	–	-	$V^0_{khói\ ẩm} + \lambda * V^0_{kk}$	11.29
Denominator	–	-	$V^0_{khói\ khô} + V^0_{kk} * \lambda$	10.39
Dry/wet oxygen ratio	-	-	$\frac{O_2^{khô}}{O_2^{ướt}} = \frac{V^0_{khói\ ẩm} + V^0_{kk}\lambda}{V^0_{khói\ khô} + V^0_{kk}\lambda}$	1.09
Wet oxygen	$O_2^{ướt}$	-		0.1335

- Table 5 determines the coefficient of excess air when dry oxygen is known. Can be converted to wet oxygen if needed.

The process of determining exhaust flue gas losses on excel tools

Table 6. Calculation of the products of actual combustion				
Types of products	**Values in Nm^3/kg of fuel**			
	Symbol	**Unit**	**Equation**	**Value**
Excess air	$V^{thừa}_{kk}$	Nm^3/kg of fuel	$V^{thừa}_{kk} = \lambda V^0_{kk}$	7.1923
Moisture in excess air	$V^{kk\ thừa}_{H2O}$	Nm^3/kg of fuel	$V^{kk\ thừa}_{H2O} = 0.00161 * d * V^{thừa}_{kk}$	0.2367
Total actual Flue gas moisture	$V^{khói}_{H2O}$	Nm^3/kg of fuel	$V^{khói}_{H2O} = V^0_{H2O} + V^{kk\ thừa}_{H2O}$	1.1325
Actual air	$V^{thực}_{kk}$	Nm^3/kg of fuel	$V^{thực}_{kk} = \alpha V^0_{kk}$	10.3919
Actual dry Flue gas	$V^{thực}_{khói\ khô}$	Nm^3/kg of fuel	$V^{thực}_{khói\ khô} = V^0_{khói\ khô} + V^{thừa}_{kk}$	10.3917
Actual Flue gas	$V^{thực}_{khói\ ẩm}$	Nm^3/kg of fuel	$V^{thực}_{khói\ ẩm} = V^0_{khói\ ẩm} + V^{thừa}_{kk}$	11.2874

- Table 6: Automatic calculation of components of real smoke and real air supply for combustion

The process of determining exhaust flue gas losses on excel tools

Table 7. Values (Ct) of the Flue gas composition by temperature					
Temperature	$(C.t)_{kk}$	$(C.t)_{CO2}$	$(C.t)_{N2}$	$(C.t)_{H2O}$	$(C.t)_{tro}$
oC	kj/ m^3 tc	kj/ m^3 tc	kj/ m^3 tc	kj/ m^3 tc	kJ/kg
100	129.95	170.03	129.58	151.02	81,0
200	261.24	357.46	259.92	304.46	169.8
300	394.89	558.81	392.01	462.72	264
400	531.2	771.88	526.52	626.16	360
500	670.9	994.35	683.8	794.85	458
600	813.36	1224.66	804.12	968.88	560
700	958.86	1431.07	947.52	1148.84	662.5
800	1090.56	1704.88	1093.6	1334.4	768
900	1256.94	1952.28	1239.84	1526.13	825
1000	1408.7	2203.5	1391.7	1722.9	985

- Table 7. Ct parameters can be looked up by temperature to determine Enthalpy exhaust smoke components. Interpolation requirements for cases of uneven temperature.

The process of determining exhaust flue gas losses on excel tools

Table 8. Calculation of heat loss due to Flue gas							
Description	Symbol	Unit	Equation	Air	RO2	N2	H2O
Flue gas composition	V	Nm^3/kg of fuel	calculated above (air is the excess air)	7.19	0.6685	2.53	1.13
Flue gas temperature	$t_{Flue\ gas}$	^{o}C	Measured	90.00	90.00	90.00	90.00
(Ct) components (specific heat x temperature)	$(Ct)_{compontents}$	kJ $^{o}C/m^3$tc	From table ˜	116.96	153.03	116.62	135.92
Enthalpy Flue gas components	$I_{component}$	kJ/kg of fuel	I = V(Ct)	841.1795025	102.2977	295.1533	153.924
Total Flue gas Enthalpy	$I_{actual\ flue\ gas}$	kJ/kg of fuel	I khói thực = I không khí + I RO2 + I N2 + I H2O	1392.554497			
Inlet air temperature	$t_{input\ air}$	^{o}C	Đo được	30			
(Ct) air inlet	$(Ct)_{input\ air}$	kJ $^{o}C/m^3$tc	Tra bảng	38.99			
Total air inlet	$V_{input\ air}$	Nm^3/kg of fuel	calculated above (air is actual total air input)	10.39			
Enthalpy Air Inlet	$I_{input\ air}$	kJ/kg of fuel	I = V (Ct)	405.1281116			
Losses due to exhaust fumes	Q2	kJ/kg of fuel	$Q_2 = (I_{khói} - V_{kk}(ct)_{kkl}(100 - q_4)$	987.426385			
Losses due to exhaust fumes	q2	%	$q_2 = \frac{Q_2}{Q_t^{lv}} = \frac{(I_{khói} - V_{kk}(ct)_{kkl}(100-q_4)}{Q_t^{lv}}$	8.126966131			

- Table 8 calculates heat loss due to exhaust fumes. (Request to look up information and interpolate the values (Ct) of exhaust smoke components from table 7)

Determination of other losses

, %

- *Heat loss due to incomplete combustion of chemistry (CO formation loss) q3*
  - $q_3 = 12600.CO\frac{V^0_{khôi\,khô}}{Q^{lv}_t}$ %
- *Heat loss due to mechanically incomplete combustion (Unburned carbon loss) q4(%)*

$$q_4 = \frac{326\left(a_x\frac{C_x}{100-C_x} + a_b\frac{C_b}{100-C_b} + a_l\frac{C_l}{100-C_l}\right)\cdot A^{lv}}{Q^{lv}_t}$$

- C_x, C_b , C_l is the percentage of carbon in slag, fly ash and penetrate through the grate, %
- a_x, a_b , a_l is the ratio of ash of fuel distributed by slag, fly ash and penetrate through the grate

Determination of other losses by Excel tool

Combustion method	Species		
	slag, a_x	Fly ash, a_b	Penetrate through grate, a_l
Step grate	0,75 - 0,85	0,20 – 0,10	0,05
Chain grate	0,75 - 0,85	0,20 – 0,10	0,05
Grate with through mechanism	0,65 – 0,75	0,30 – 0,20	0,05
Fluidization	0,50 – 0,60	0,50 – 0,40	-
Pulverization	0,10 – 0,20	0,90 – 0,80	-

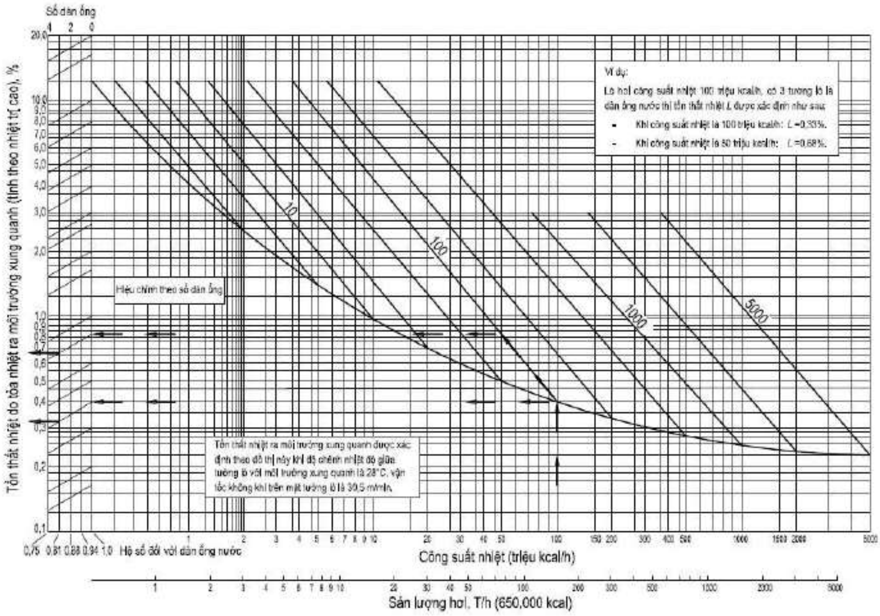
Notes:

- *When choosing in the table need to meet the condition $a_x + a_b + a_l = 1$*
- *For oil-fired and gas-fired boilers, $q_4 = 0$.*

- ***Heat loss due to radiation and convection to the surrounding environment q_5***
- *Q5 can be determined by measuring the surface temperature and making calculations as presented in the main lecture. Or we can look up the graph in case of rated load. When the operating load is less than the rated power, q5 increases and is determined by the formula:*

$$q_5^x = q_5\frac{D}{D_x} \quad \%$$

- *Where D = Nominal load*
- *Dx = Operating load*



Graph of determination of heat loss to the surrounding environment

Determination of other losses by Excel tool

Temperature, °C	Specific heat capacity, kJ/kg °C	Temperature, °C	Specific heat capacity, kJ/kg °C	Temperature, °C	Specific heat capacity, kJ/kg °C
100	0,805	800	0,957	1500	1,117
200	0,844	900	0,970	1600	1,117
300	0,876	1000	0,983	1700	1,214
400	0,900	1100	0,995	1800	1,214
500	0,915	1200	1,002	1900	1,254
600	0,933	1300	1,004	2000	1,254
700	0,954	1400	1,113		

- ***Heat loss due to slag carried out of the boiler q6***

$$q_6 = \frac{a_x A^{lv} c_x t_x}{Q_t^{lv}} \quad \%$$

- Where:
  - a_x is the ratio of ash of fuel distributed by slag
  - t_x is the temperature of the slag discharged from the furnace, ^oC
  - c_x is the specific heat of slag as determined according to the Table below, kJ/kg ^oC

Determination of other losses by Excel tool

Heat loss due to CO formation q3			
Description	Symbol	Unit	Value
Measured CO content	CO ppm	ppm	300
Measured CO content	CO %	%	0.03
Theoretical dry Flue gas volume	$V^0_{khói\ khô}$	m3tc/kg	3.20
Low heating value working sample	Q^{lv}_t	kJ/kg	12150
Heat loss due to CO formation q3	q3	%	0.1

Heat loss due to unburned carbon in Ash q4			
Description	Symbol	Unit	Value
The proportion of fly ash in the total amount of ash	ab	%	10
The rate of bottom slag discharged	ax	%	85
Percentage of penetration through grate	al	%	5
Unburned carbon content in fly ash	Cb	%	15
Unburned carbon content in bottom slag	Cx	%	10
Unburned carbon content in the penetration through grate	Cl	%	40
Ash content in fuel	Alv	%	0.15
Heat losses due to mechanical incomplete fire	Q4	kJ/kg	711.13
Low heating value working sample	Q^{lv}_t	kJ/kg	12150.00
Heat losses due to mechanical incomplete fire	q4	%	5.853

Determination of other losses by Excel tool

Convection and radiation loss q5			
Description	Symbol	Unit	Value
Boiler power at rated load	D	Tấn hơi/h	10
The operating capacity of the furnace	Dx	Tấn hơi/h	5
Losses due to Convection and radiation at nominal loads	q5	%	0.5
Losses due to Convection and radiation at operation loads	q5	%	1

Convection and radiation loss q5 (tcalculated by temperature measurement of surfaces)						
Description	Symbol	Unit	Front surface	Back surface	Left side	Right side
Ambient temperature	ta	°C	30	30	30	30
Boiler shell temperature	tv	°C	52.0	52.0	52.0	52.0
Area	A	m^2	19	19	18	18
Heat transfer coefficient	H	W/m^2	219.1	219.1	219.1	219.1
The amount of heat on surfaces	Q	W	4,073	4,073	3,948	3,948
Total boiler surface heat	Qtotal	kW				16
Fuel consumption	B	kg/h				667
Low heating value working sample	Q^{lv}_t	kJ/kg				12,150
Total furnace grade heat	Qc	kW				2,251
Convection and radiation loss q5	q5	**%**				**0.71**

Determination of other losses by Excel tool

Losses due to slag discharge			
Description	**Symbol**	**Unit**	**Value**
Waste slag rate	ax	%	85
Ash content in fuel	Alv	%	0.15
Waste slag temperature	tx	oC	600
Waste slag specific heat	Cx	kJ/kgoC	0.933
Heat loss due to waste slag	Q6	kJ/kg	0.71
Calorific value of fuel	Q^{lv}_{t}	kJ/kg	12150
Heat loss due to waste slag	q6	%	0.01

Boiler efficiency by direct method			
Description	**Symbol**	**Unit**	**Value**
Steam pressure	P	bar	10
Output of steam produced	D	Tấn/h	10
Fuel consumption	B	Tấn/h	2.5
Low calorific value of fuel	Q^{lv}_{t}	kJ/kg	12150
Inlet water temperature	tn	oC	80
Enthalpy Water Inlet	hn	kJ/kg	334.88
Enthalpy steam produced (table tea)	hh	kJ/kg hơi	2777.5
The amount of useful heat generated	Q1	kJ/h	24426200
Input heat	Qv	kJ/h	30375000
Boiler efficiency according to forward balance	**η**	**%**	**80.4**

Hiệu suất lò hơi theo phương pháp cân bằng nghịch (gián tiếp)			
Description	**Symbol**	**Unit**	**Value**
Loss due to flue gas	q2	%	8.1
Loss due to CO formation	q3	%	0.1
Loss due to unburned carbon in ash	q4	%	5.853
Convection and radiation loss	q5	%	1
Slag discharge loss	q6	%	0.01
Boiler efficiency by indirect methoc	**η**	**%**	**84.91**

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Section 10: Steam System Optimization – Wrap Up

- MEASUR Assessment Report
- Conclusions
- Tools & Resources

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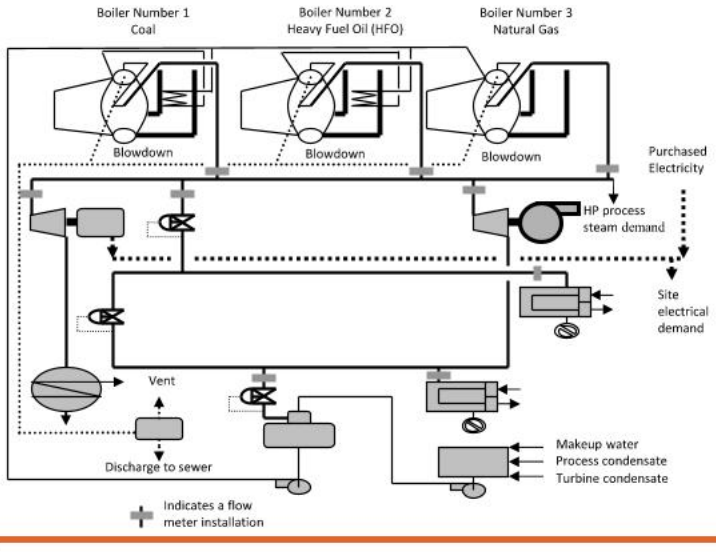

Steam System

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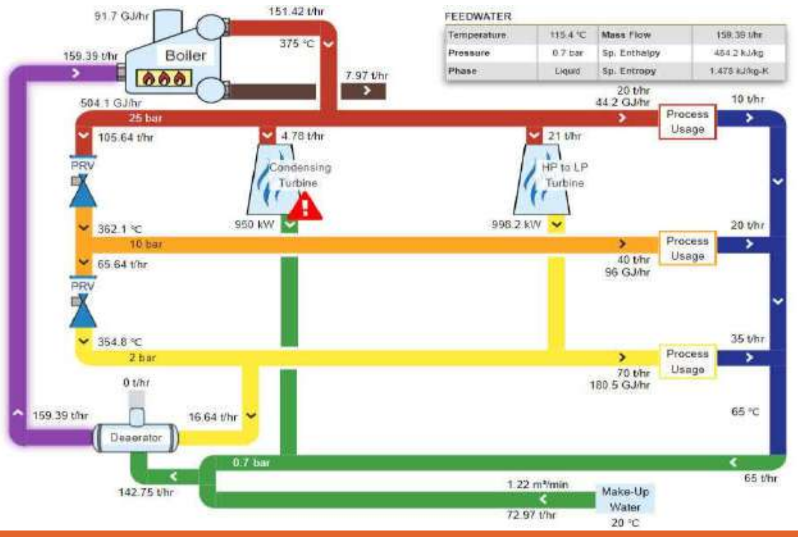

Example Steam System

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Example Steam System

COST SUMMARY

Power Balance	
Generation	1,948.2 kW
Demand	6,948.2 kW
Import	5,000 kW
Unit Cost	$0.10 /kWh
Total $/yr	$4,380,000

Fuel Balance	
Boiler	504.12 GJ/hr
Unit Cost	$25.00 /GJ
Total $/yr	$110,402,099

Make-Up Water	
Flow	1.22 m³/min 640,361.2 m³
Unit Cost	$0.66 /m³
Total $/yr	$422,638

Total Operating Cost
$115,204,737

MARGINAL STEAM COST

High Pressure	$93.89 /t
Medium Pressure	$93.89 /t
Low Pressure	$93.72 /t

Example Steam System – Summary Report

Steam Example
Last Modified 9/13/22, 8:36 AM

Print

Executive Summary | Energy Summary | Losses | Diagram | Report Graphs | Input Summary | Facility Info | Sankey

	Baseline	Reduce Blowdown	Blowdown Energy Recovery	Steam Leak	Insulation	Steam Demand	Condensate Return	Condensate Flash Tanks	HP-LP Turbine	Condensing Turbine
Percent Savings (%)	—			—	—		—		—	
Power Cost ($/yr)	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	3,505,618	5,212,200
Savings	—	0	0	0	0	0	0	0	874,382	-832,200
Fuel Cost ($/yr)	110,402,099	109,239,628	108,574,166	110,380,690	110,303,818	109,508,157	110,252,531	107,842,608	111,495,512	106,556,490
Savings	—	1,162,471	1,827,933	21,409	98,281	893,941	149,568	2,559,491	-1,093,413	3,845,609
Make-up Water Cost ($/yr)	422,638	394,319	413,938	422,554	422,250	419,096	405,676	423,173	426,292	421,049
Savings	—	28,319	8,701	85	388	3,542	16,963	-535	-3,653	1,589
Annual Cost ($)	**115,204,737**	**114,013,947**	**113,368,104**	**115,183,243**	**115,106,068**	**114,307,254**	**115,038,207**	**112,645,781**	**115,427,422**	**112,189,739**
Annual Savings ($)	—	**1,190,790**	**1,836,633**	**21,494**	**98,669**	**897,483**	**166,531**	**2,558,956**	**-222,685**	**3,014,999**
Implementation Cost	—	—	—	—	—	—	—	—	—	—
Payback Period (months)	—	—	—	—	—	—	—	—	—	—
Selected Energy Projects	—	Adjust Boiler Operations	Adjust Boiler Operations	Adjust Steam Demand/Usage	Modify High to Low Pressure Steam Turbine	Adjust Steam Demand/Usage	Adjust Condensate Handling	Adjust Condensate Handling		Modify High Pressure to Condensing Steam Turbine
Modifications	—	Boiler	Boiler	Header	Header	Header	Header	Header	Turbine	Turbine

Example Steam System – Sankey Plot

Steam Example
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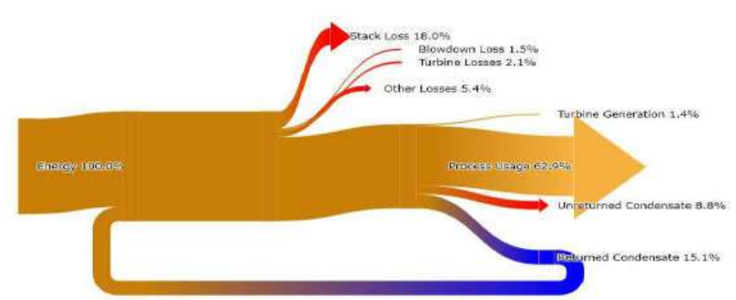
Executive Summary | Energy Summary | Losses | Diagram | Report Graphs | Input Summary | Facility Info | Sankey

Baseline

Cost Savings: $0/yr



* Other Losses include: High Pressure Header, Medium Pressure Header, Low Pressure Header, Condensate, Deaerator Vent, Condensate Flash Tank

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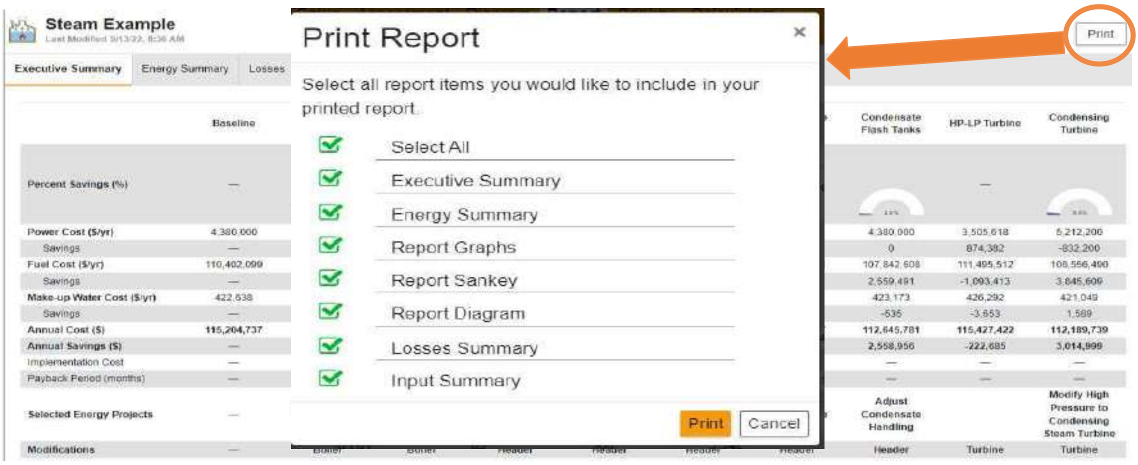
Example Steam System – Summary Report



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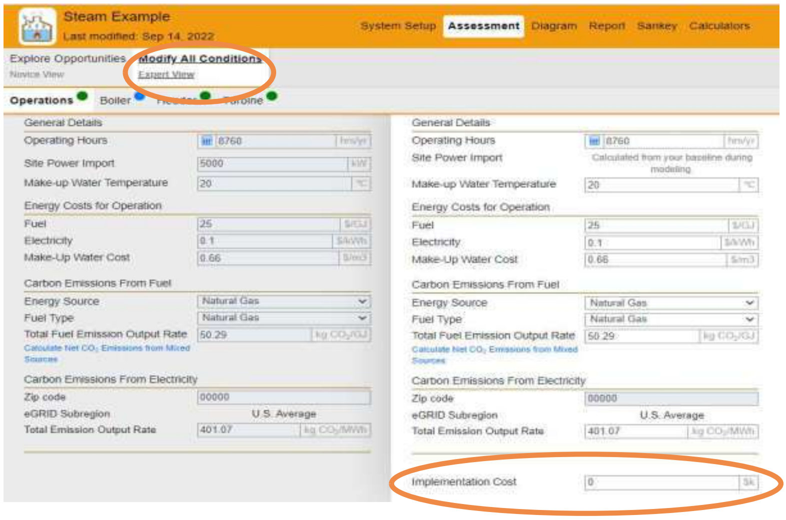

Example Steam System – Expert View

- Be very careful
- Allows maximum flexibility to modify all conditions
- Cost of implementation – no check for accuracy

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Example Steam System – Summary Report

Steam Example

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Executive Summary | Energy Summary | Losses | Diagram | Report Graphs | Input Summary | Facility Info | Sankey

	Baseline	Reduce Blowdown	Blowdown Energy Recovery	Steam Leak	Insulation	Steam Demand	Condensate Return	Condensate Flash Tanks	HP-LP Turbine	Condensing Turbine
Percent Savings (%)	—	[illegible]	[illegible]	—	—	[illegible]	—	[illegible]	—	[illegible]
Power Cost ($/yr)	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	4,380,000	3,505,618	5,212,200
Savings	—	0	0	0	0	0	0	0	874,382	-832,200
Fuel Cost ($/yr)	110,402,099	109,239,628	108,574,166	110,380,690	110,303,818	109,508,157	110,252,531	107,842,608	111,495,512	106,556,490
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Implementation Cost	—	—	—	—	—	—	—	—	—	—
Payback Period (months)	—	—	—	—	—	—	—	—	—	—
Selected Energy Projects	—	Adjust Boiler Operations	Adjust Boiler Operations	Adjust Steam Demand/Usage	Modify High to Low Pressure Steam Turbine	Adjust Steam Demand/Usage	Adjust Condensate Handling	Adjust Condensate Handling		Modify High Pressure to Condensing Steam Turbine
Modifications	—	Boiler	Boiler	Header	Header	Header	Header	Header	Turbine	Turbine

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Conclusions

Key Points / Action Items - Fundamentals

1. Use a Systems Approach to optimize steam systems
2. There are four major areas of a steam system – Generation, Distribution, End-Use & Recovery
3. An understanding of the laws of thermodynamics, heat transfer, fluid flow and steam properties is required for a steam system analysis
4. Use a systematic approach (gap analysis, comparison to BestPractices) to identify potential energy saving opportunities that may exist in steam systems

Key Points / Action Items – Boiler Efficiency

1. Determine boiler plant operating cost
2. Determine unit cost of steam generation
3. Determine boiler operating efficiency

$$\eta_{boiler} = \frac{m_{steam}\left(h_{steam} - h_{feedwater}\right)}{m_{fuel}\, HHV_{fuel}} \times 100$$

4. There are three major losses in steam generation – shell loss, blowdown loss and stack loss

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

Key Points / Action Items – Shell Loss

1. Search for "hot spots"
2. Measure boiler surface temperatures
   - Infrared thermography
   - Typical surface temperature should range between 55°C and 70°C
3. Repair refractory
4. Monitor surface cladding integrity
5. Reduced boiler load can present an opportunity
   - Minimize number of operating boilers

Key Points / Action Items – Blowdown Loss

1. Estimate amount of blowdown using boiler and feedwater conductivities
2. Quantify the boiler and system-level energy loss due to blowdown
3. Evaluate installation of an automatic blowdown controller
4. Evaluate and install flash steam and heat recovery equipment
5. Work closely with plant's water chemists to maintain and manage appropriate blowdown

Key Points / Action Items – Stack Loss

1. Monitor and record flue gas temperature with respect to:
   - Boiler load
   - Ambient temperature
   - Flue gas oxygen content
2. Compare flue gas temperature to previous, similar operating conditions
3. Maintain appropriate fire-side cleaning
4. Maintain appropriate water chemistry
5. Evaluate heat recovery component savings potential

Key Points / Action Items – Stack Loss

1. Combustion management principles:
   - Add enough oxygen to react all of the fuel
   - Minimize the amount of extra air
   - Monitor combustibles to identify problems
2. Measure the oxygen content of boiler exhaust gas
3. Control oxygen content within a minimum and maximum range
   - Continuous - automatic O_2 trim control
   - Positioning control
4. Challenge the control range
   - Control upgrade
   - Combustion tuning

Key Points / Action Items – Boiler Plant Optimization

1. Use a steam system model based on the laws of thermodynamics to quantify energy and cost savings opportunities
2. Fuel switching and boiler plant operations are excellent areas for optimization of steam systems – significant cost savings can be realized by applying optimal operating strategies
3. Each application will need an independent evaluation – there are NO thumb rules!

Key Points / Action Items – Leaks

1. Steam leaks occur in all plants and a continuous improvement type steam leak management program should be implemented in industrial plants
2. An "order of magnitude" steam loss estimate can provide enough information to determine if the repair must be made immediately, during a future shutdown, or online

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Key Points / Action Items - Insulation

1. There are several reasons for damaged or missing insulation
2. These areas result in significant energy losses and a continuous improvement type insulation appraisal (audit) program should be implemented in industrial plants
3. Some basic instruments, heat transfer models and process data are required to quantify the economic impact of missing or damaged insulation

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Key Points / Action Items – End Use

1. There are several end-uses of steam in industrial plants
2. Do a steam end-use balance in an industrial plant and identify the largest steam end-users in a plant
3. Reduce steam end-use by
   - Improving the efficiency of the process
   - Shifting steam demand to a waste heat source or lower pressure steam available in the plant

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Key Points / Action Items – Process/Utility Integration

1. Upgrade low pressure (or waste) steam to supply process demands
2. Several plants need heating and cooling for process
3. Process integration can lead to significant energy savings opportunities and plant optimization
4. These opportunities will need significantly higher amounts of due-diligence

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Key Points / Action Items – Steam Traps

1. There are different kinds of steam traps and hence, functionality and principles of operation must be understood
2. Major steam trap failure modes - open / closed
3. An effective steam trap management program must be in place
4. There are several commercially available tools for steam trap investigations
5. Conduct a steam trap audit at least once a year and repair/replace defective traps
6. Steam trap manufacturers are a valuable resource

Key Points / Action Items – Condensate Recovery

1. Returning condensate
   - Reduces energy
   - Reduces make-up water
   - Reduces chemicals for water treatment
   - Reduces quenching water
   - May reduce blowdown
2. Condensate recovery is often neglected but it can provide significant energy savings
3. Quantify the amount of condensate being recovered in a plant using a simple mass balance on the entire steam system
4. Identify potential areas of condensate recovery

Key Points / Action Items – Backpressure Turbines

1. Backpressure turbines are used instead of pressure letdown stations
2. Turbine efficiency is NOT 1st law efficiency but a comparison of actual turbine versus an ideal turbine
3. Continuous operations with a simultaneous thermal and electric demand are good candidates for backpressure turbines
4. Each facility analysis is unique and will depend on several economic as well as operating factors
5. Turbine analysis will need a solid thermodynamic steam system model

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Key Points / Action Items – Condensing Turbines

1. Condensing turbines are used strictly for power generation or driving large mechanical equipment
2. They serve niche applications in the industry
3. Condensing turbines provide maximum shaft power per unit of steam flow
4. Each facility analysis is unique and will depend on several economic as well as operating factors
5. Turbine analysis will need a solid thermodynamic steam system model

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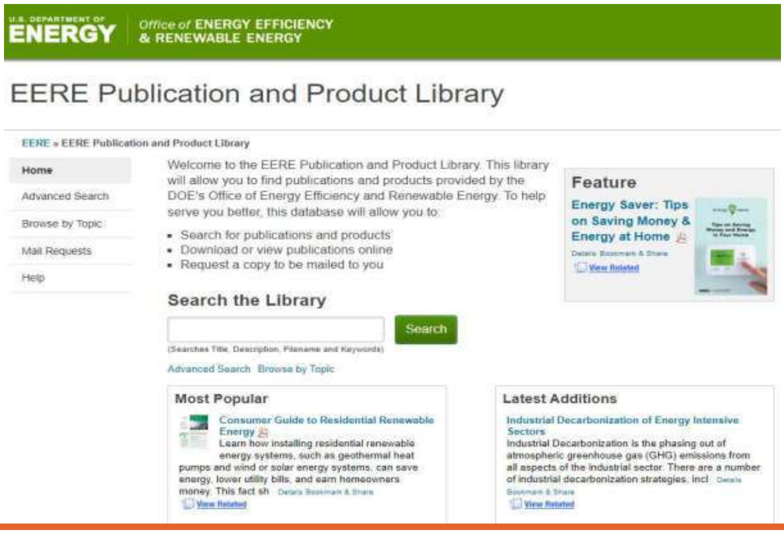
Tools & Resources

Tools

- In order to properly evaluate steam systems the physics of each process must be understood
  - Thermodynamics
  - Heat transfer
  - Fluid flow
- UNIDO Steam System Optimization 2-day EndUser Training Manual
- US DOE Tools Suite
  - Steam System Survey Guide
  - Steam System Scoping Tool (SSST)
  - MEASUR (Desktop & Online versions)
  - Insulation evaluation software – 3E-Plus (Desktop & Online versions)
- Several other commercially available software tools for steam systems
- Process measurements

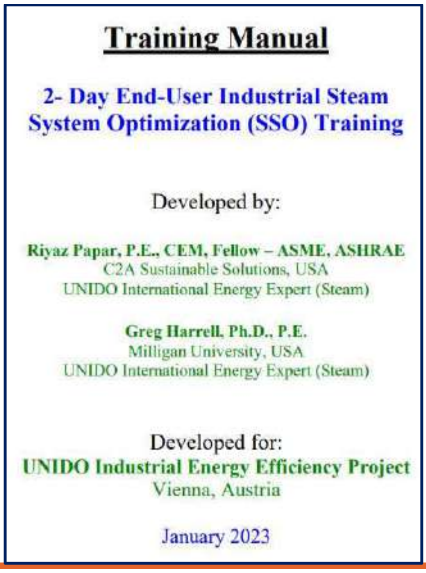
Where to go for the Tools

- US DOE website for downloading - https://www.energy.gov/eere/amo/measur
- Online version - http://measur.ornl.gov



Technical Publications & Resources

- http://www.energy.gov/eere/publications



Training Manual

2- Day End-User Industrial Steam System Optimization (SSO) Training

Developed by:

Riyaz Papar, P.E., CEM, Fellow – ASME, ASHRAE
C2A Sustainable Solutions, USA
UNIDO International Energy Expert (Steam)

Greg Harrell, Ph.D., P.E.
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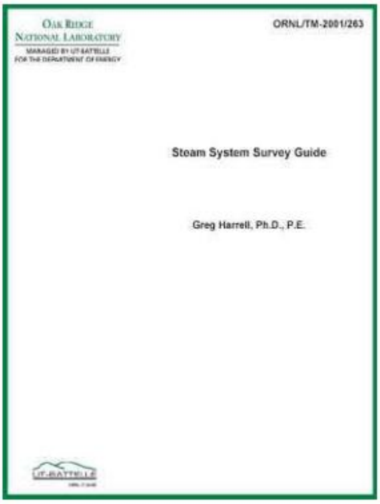
Developed for:
UNIDO Industrial Energy Efficiency Project
Vienna, Austria

January 2023

2-Day End-User Industrial Steam System Optimization (SSO) Training Manual

- Developed by UNIDO
- Text-book for the 2-day SSO training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MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

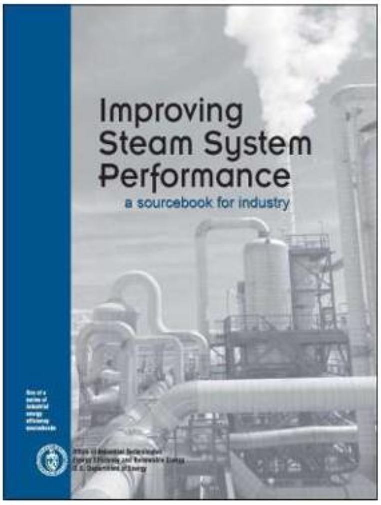
ORNL/TM-2001/263

Steam System Survey Guide

Greg Harrell, Ph.D., P.E.

Steam System Survey Guide

- Technical Guide
- Covers 5 Areas:
  - Steam system profiling
  - Identifying steam properties
  - Improving boiler operations
  - Improving resource utilization
  - Improving steam distribution



Steam System Sourcebook

- Includes Three Main Sections:
  - Steam System Basics
  - Performance Improvement Opportunities
  - Programs, Contacts, and Resources


Energy Tips

Replace Pressure-Reducing Valves with Backpressure Turbogenerators

Cost-Effective Power Generation

Suggested Actions

Applicability

Estimating Your Savings

Steam Energy Tips

- 1- Page Tips For Improving Steam System Areas
- Available On BestPractices Web Site and in Steam Sourcebook

US DOE Tip Sheets

- Benchmark the Fuel Cost of Steam Generation
- Clean Boiler Water-side Heat Transfer Surfaces
- Consider Installing a Condensing Economizer
- Consider Installing High-Pressure Boilers with Backpressure Turbine-Generators
- Consider Installing Turbulators on Two- and Three-Pass Firetube Boilers
- Consider Steam Turbine Drives for Rotating Equipment
- Considerations When Selecting a Condensing Economizer

US DOE Tip Sheets (cont.)

- Cover Heated, Open Vessels
- Deaerators in Industrial Steam Systems
- Flash High-Pressure Condensate to Regenerate Low-Pressure Steam
- Inspect and Repair Steam Traps
- Install an Automatic Blowdown Control System
- Install Removable Insulation on Valves and Fittings
- Insulate Steam Distribution and Condensate Return Lines

US DOE Tip Sheets (cont.)

- Improve Your Boiler's Combustion Efficiency
- Minimize Boiler Blowdown
- Minimize Boiler Short Cycling Losses
- Recover Heat from Boiler Blowdown
- Replace Pressure-Reducing Valves with Backpressure Turbogenerators
- Return Condensate to the Boiler

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US DOE Tip Sheets (cont.)

- Upgrade Boilers with Energy-Efficient Burners
- Use Feedwater Economizers for Waste Heat Recovery
- Use Low Grade Waste Steam to Power Absorption Chillers
- Use Steam Jet Ejectors or Thermocompressors to Reduce Venting of Low-Pressure Steam
- Use Vapor Recompression to Recover Low-Pressure Waste Steam
- Use a Vent Condenser to Recover Flash Steam Energy

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US DOE Technical Documents

- Improving Steam System Performance: A Sourcebook for Industry
- Achieve Steam System Excellence: Industrial Technologies Program BestPractices Steam Overview Fact Sheet
- BestPractices Steam Technical Brief: Steam Pressure Reduction-Opportunities and Issues
- BestPractices Steam Technical Brief: How to Calculate the True Cost of Steam
- BestPractices Steam Technical Brief: Industrial Heat Pumps for Steam and Fuel Savings
- BestPractices Steam Technical Brief: Industrial Steam System Heat-Transfer Solutions

US DOE Technical Documents (cont.)

- BestPractices Steam Technical Brief: Industrial Steam System Process-Control Schemes
- Guide to Combined Heat and Power Systems for Boiler Owners and Operators
- Guide to Low-Emission Boiler and Combustion Equipment Selection
- Review of Orifice Plate Steam Traps

Course Evaluation & Feedback

Your input is greatly appreciated and it will be acted upon to refine this training program as well as better tailor further complementary technical assistance to be offered by the UNIDO project to industrial plants and enterprises

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